Supplementary Material

Table S.1 Author contact information and contribution (SCM- steering committee member, WWGL – workshop Writing Group lead, WWGP - workshop and Writing Group participant). All WWGP participated in document writing, review and revision.[1]

MAHLON C. KENNICUTT II (Co-convener, Co-Chair Steering Committee, Workshop leader, primary and corresponding author, WWGP), Texas A&M University, College Station, Texas, USA

YEADONG KIM (Co-convener, Co-Chair Steering Committee, WWPG), Korean Polar Research Institute, Incheon, Republic of Korea

MICHELLE ROGAN-FINNEMORE (Project Manager, secondary author, document editor, WWPG), COMNAP Secretariat, Christchurch, New Zealand

SRIDHAR ANANDAKRISHNAN (SCM, WWGL WWPG), Pennsylvania State University, University Park, Pennsylvania, USA

STEPHEN F. ACKLEY (WWPG), University of Texas San Antonio, San Antonio, Texas, USA

NICOLE BIEBOW (WWPG), PolarNet Project Office, Bremerhaven, Germany

DON BLANKENSHIP (SCM, WWGL, WWWPG) University of Texas at Austin, Austin, Texas, USA

SUN BO (WWPG), Polar Research Institute of China, Shanghai, China

JENNY BAESEMAN (WWPG), Scientific Committee on Antarctic Research Secretariat, Cambridge, England

CÉSAR A. CÁRDENAS (WWPG), Instituto Antártico Chileno, Punta Arenas, Chile

JOHN J CASSANO (WWPG), University of Colorado, Boulder, Colorado, USA

STEVEN L. CHOWN (WWGL, WWPG), Monash University, Victoria, Australia

STEVEN COLWELL (WWGL, WWPG), British Antarctic Survey, Cambridge, England

DON A. COWAN (WWGL, WWPG), University of Pretoria, Pretoria, South Africa

CHEN DANHONG (WWPG), Chinese Arctic and Antarctic Administration, Beijing, China

JUAN JOSE DAÑOBEITIA (WWPG), Unidad de Tecnologia Marina, Barcelona, Spain

CARLOTA ESCUTIA (WWGL, WWPG), Instituto Andaluz de Ciencias de la Tierra, Armilla, Spain

JANE FRANCIS (SCM, WWPG), British Antarctic Survey, Cambridge, England

[1] The Council of Managers of Antarctic Programs (COMNAP) or individual authors do not endorse or recommend any commercial products, processes, or services nor does it grade or rank specific research programs. The mention or inclusion of a photograph in this publication, in the surveys, or in any of the Antarctic Roadmap Challenges (ARC) discussions and outcomes is not an endorsement or recommendation from COMNAP, any of the COMNAP Member national Antarctic programs or individuals. ARC project outcomes are provided to assist with better understanding of possible future Antarctic research directions. The designations employed, including any geographic names, and the presentations in this article do not imply the expression of any opinion on the part of COMNAP or individual authors concerning the legal status of any of those names: of a country, territory, feature or authority.

YVES FRENOT (SCM, WWGL, WWPG), Institut polaire français Paul-Emile Victor, Plouzané, France

JOHN E. GULDAHL (WWPG), Norwegian Polar Institute, Tromsø, Norway

JOHN HALL (WWGL WWPG), British Antarctic Survey, Cambridge, England

GEN HASHIDA (WWPG), National Institute of Polar Research, Tachikawa, Japan

LAUTARO JIMÉNEZ CORBALÁN (WWPG), Antarctic Logistics Division, Buenos Aires, Argentina

ALEXANDER KLEPIKOV (WWPG), Arctic and Antarctic Research Institute, St Petersburg, Russia

JOOHAN LEE (WWPG), Korean Polar Research Institute, Incheon, Republic of Korea

MARCELO LEPPE (SCM, WWPG), Instituto Antártico Chileno, Punta Arenas, Chile

DANIELA LIGGETT (WWGL, WWPG), University of Canterbury, Christchurch, New Zealand

FANG LIJUN (WWPG), Chinese Arctic and Antarctic Administration, Beijing, China

JERONIMO LÓPEZ-MARTINEZ (SCM, WWPG)), Universidad Autónoma de Madrid, Madrid, Spain

ADRIAN MCDONALD (WWGL, WWPG), University of Canterbury, Christchurch, New Zealand

MARIANO MEMOLLI (WWPG), Dirección Nacional del Antártico, Buenos Aires, Argentina

HEINRICH MILLER (SCM), Alfred Wegener Institute, Bremerhaven, Germany

YOICHI MOTOYOSHI (WWPG), National Institute of Polar Research, Tachikawa, Japan

RODRIGO MOUSALLE BUENO (WWPG), Programa Antártico Brasileiro, Brasilia, Brazil

JAVIER NEGRETE (WWPG), Instituto Antártico Argentino/ Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata, Argentina

UWE NIXDORF (WWGL, WWPG), Alfred Wegener Institute, Bremerhaven, Germany

MIGUEL A. OJEDA CÁRDENES (WWPG), Consejo Superior de Investigaciones Científicas, Barcelona, Spain

MARIO PROAÑO SILVA (WWPG), Ecuadorian Antarctic Institute, Guayaquil, Ecuador

SONIA RAMOS-GARCIA (WWPG), Spanish Polar Committee Technical Secretariat, Madrid, Spain

STEVE RINTOUL (SCM), Commonwealth Scientific and Industrial Research Organization Antarctic Climate & Ecosystems Cooperative Research Centre, Hobart, Tasmania

HERNÁN E. SALA (WWPG), Instituto Antártico Argentino - Dirección Nacional del Antártico, Buenos Aires, Argentina

HYOUNG CHUL SHIN (WWPG), Korean Polar Research Institute, Incheon, Republic of Korea

XU SHIJIE (WWPG), Chinese Arctic and Antarctic Administration, Beijing, China

KAZUYUKI SHIRAISHI (SCM, WWPG)), National Institute of Polar Research, Tachikawa, Japan

MARTIN J. SIEGERT (WWGL, WWPG), Imperial College London, London, England

TIM STOCKINGS (WWPG), British Antarctic Survey, Cambridge, England

SIMON TROTTER (WWPG), Antarctica New Zealand, Christchurch, New Zealand

DAVID G. VAUGHAN (WWPG), British Antarctic Survey, Cambridge, England

JOSÉ AUGUSTO VIERA DA UNHA DE MENEZES (WWPG), Programa Antártico Brasileiro, Brasilia, Brazil

VERÓNICA VLASICH (WWPG), Dirección Nacional del Antártico, Buenos Aires, Argentina

ANNA WÅHLIN (WWGL, WWPG), University of Gothenburg, Gothenburg, Sweden

QIN WEIJIA (WWPG), Chinese Arctic and Antarctic Administration, Beijing, China

TERRY WILSON (WWGL, WWPG), Ohio State University, Columbus, Ohio, USA

GARY WILSON (WWGL, WWPG), New Zealand Antarctic Research Institute, Christchurch, New Zealand

JAN-GUNNAR WINTHER (WWPG), Norwegian Polar Institute, Tromsø, Norway

ROBERT E. WOODING (WWGL, WWPG), Australian Antarctic Division, Hobart, Tasmania, Australia

HUIGEN YANG (SCM), Polar Research Institute of China, Shanghai, China

HORIZON SCAN CLUSTER 1:
Antarctic Atmosphere and Global Connections

ARC Workshop Writing Group Participants

Co-leads: Adrian McDonald & Robert E. Wooding
Nicole Biebow, John J. Cassano, Steven Colwell (Scribe), Kelly Falkner, Fang Lijun, Paul Sheppard, Tim Stockings, Qin Weijia

Scientific Questions	*"Changes in Antarctica's atmosphere alter the planet's energy budgets, temperature gradients, and air chemistry and circulation. Too little is known about the underlying processes. How do interactions between the atmosphere, ocean and ice control the rate of climate change? How does climate change at the pole influence tropical oceans and monsoons? How will the recovering ozone hole and rising greenhouse-gas concentrations affect regional and global atmospheric circulation and climate" (Kennicutt et al., 2014 Nature COMMENT).* While the Horizon scan questions are all important without prioritization of questions it is difficult to prioritize the highest priority technological advances. Societal relevance was deemed important as well as the advancement of science. Integration across all questions is important as there are many interconnections between clusters. Expertise within the group limited detailed discussions of paleoclimate related questions. Q72 and Q73 were also somewhat out of the group's expertise, as were Q3, Q5, Q9, and Q53.	
Highest Priority Technological Advances		
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Observing technology capable of being optimally deployed, sustained autonomously including power requirements.	H
	2. Improved satellite remote sensing.	H
	3. Data transfer in real time.	H
	4. Improved Earth System Modelling for weather and climate modelling and system re-analysis.	H
	5. Improved exchange of people and information across national Antarctic program.	H
Estimation of the current status of the **technology**	1. Mixture of mature and emerging technologies.	H
	2. More deployment of existing sensors required plus some further development.	H
	3. Exists, but not adequately deployed in Antarctica.	H
	4. Mixture of existing and emerging capabilities.	H
	5. Channels already exist, but require strengthening.	H
	Comments: Lessons can be learned from the Arctic community which are ahead in some areas.	
At what temporal scales will these **technologies** most likely be used and how frequently?	1. continuous	H
	2. continuous	H
	3. continuous	H
	4. continuous	H
	5. Increased frequency	H
	Comments: For satellite remote sensing, the continuity of satellite operation is important for climate and ozone records. Atmospheric processes have short time scale and operational links, thus near real time information is important.	

What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Logistics costs of deployment and maintenance are high, so enhanced technology development, although expensive, will improve the observing network and possibly achieve cost savings. Spectrum from 10k to 10M	High
	2. Difficult to identify cost – polar science and operations need to be at the table throughout the time that satellite projects are being developed and implemented	
	3. Polar targeted satellites – 10s of millions. Cheaper alternatives (e.g., Google Project Loon as a communication platform) are under development. Potential to access	
	4. Millions of dollars	
	5. Low-cost: requires active coordination between programs and a will to do it. Coordination between data centers will be important. The costs of investing in this will produce equal or greater benefits.	
	Comments: Satellite specific: COMNAP needs to engage with Experts on Polar and High Mountain Observations, Research and Services. Balance of creation to usage costs and processing for satellite work is important. Polar science giving input to European Space Agency, NASA and other national space agencies.	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	The range of technologies identified are broad and cover most of the questions in this cluster, e.g. Q1, Q2, Q4, Q6, Q7, Q10 and Q11 The technologies identified are more relevant to 'atmospheric' rather than 'paleoclimate' questions.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Satellite development/deployment and ESM development is beyond the capabilities of the Antarctic community. Both need to connect to major other players, (NASA and other space agencies). Development of battery technologies and Unmanned Air Systems are beyond Antarctic community. Both of the latter will benefit from commercial applications/developments.	
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Google Project Loon could be used as an alternative to satellite communications potentially Unmanned Air Systems have not been fully examined in the Antarctic community.	

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority technological needs to accomplish the science of this cluster.	Avoidance of higher cost solutions may not save money long-term. Prioritization based on achievability scientific pay-off. 1. Observing technology capable of being optimally deployed, sustained autonomously, including power requirements. 2. Improved satellite remote sensing 3. Data Transfer in real time 4. Improved Earth System Models 5. Improved exchange of people and information across national Antarctic programs The group considered these to be of equal priority. Discussions were wide-ranging and initially discussed the different questions and their possible technological needs. The survey results were also discussed in terms of their relevance to particular questions. After some discussion it was clear that two of the priorities in the list identified in the survey results, namely 'Continuous measuring sensors' and 'Remote weather stations with expanded and robust sensor arrays' were likely best grouped together because of the intrinsic linkage between Automated Weather Systems and continuous measurements. Technologies for smart deployment are important. Consensus was that many (if not all) questions could be tackled via the use of improved modeling. However, there was significant discussion on whether 'improved climate modelling' was a technological need or a science question. After some debate and examination of the survey results, which showed poor availability of this technology (86% identifying no access), the technology requirement might be considered to be stronger cyberinfrastructure, namely High Performance Computing requirements and the development of relevant databases. 'Improved climate modelling' was changed to 'Improved Earth System modelling' given that developments in this area are moving in this area. An Earth System Model expands the range of the components in the climate system modelled (e.g. adding biosphere, cryosphere). In addition, this change also allows some questions in the Horizon Scan to be tackled (in particular Q4, Q6, Q7 and Q11) also cross-cutting questions (Q19, Q72). Without this broader definition these questions probably cannot be addressed. A significant technological need was to enhance some aspects of logistics with improved operational weather forecasting, thus Q7 in the Horizon Scan is a science question has strong linkages to logistic operations. One member of the group identified that 'it is clear that the Antarctic programs with the best forecasting capabilities completed more work'. There is also considerable replication of this effort amongst national programs. The vital importance of sea ice forecasting logistically was also mentioned, as was connecting to the Arctic community. The World Meteorological Organization's Experts on Polar and High Mountain Observations group was identified as focusing on improving models and data availability. Remote sensing will be a critical technology for answering many questions (Q1, Q2, Q4, Q11). In relation to 'advanced data analysis' a result from Survey 1, improved connectivity (higher bandwidth connections and connecting people) and power technology (a mixture of improved technologies for energy generation/storage and minimization of energy requirements for autonomous systems is absolutely crucial on logistics side) are important. There is a need for 'improved exchange of people and information' – the former may be related to better coordination of the logistic pool, and the latter might be about technology transfer and also better information dispersal and linkages across databases. There was also discussion on the need for deep-ocean drilling for paleo-climate relevant questions but details were uncertain given the group's expertise and these issues are considered by other groups.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Southern Ocean and sub-Antarctic islands	
	2. West Antarctic ice shelf (W)	
	3. The least accessible regions of the Antarctic interior	
	4. Sea ice zone	
	5. Opportunistic access to all areas	
	Comments: Collaboration is becoming more critical between providers. Opportunities were identified – e.g., EU-PolarNet – to link logistics understanding and capability and this could be relevant to future access.	
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. See logistics and infrastructure costings. Millions of dollars per ship voyage, hundreds of thousands to millions of dollars per traverse/aviation activity.	
	2. Hundreds of thousands to millions per traverse/aviation activity.	
	3. Hundreds of thousands to millions per traverse/aviation activity.	
	4. Icebreakers – millions per voyage.	
	5. Low cost – transfer of equipment and knowledge to a science or logistics team visiting a particular area.	
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	The regions identified support all 11 atmospheric science questions.	
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **accessed** to accomplish the science of this cluster.	Many questions are linked to teleconnections at hemispheric scale, and can only be addressed through broader sampling from a larger range of areas, including large parts of the Southern Ocean, the West Antarctic ice shelf and some of the least accessible inland parts of East Antarctica and Dronning Maud Land. The last of these areas feature the most extreme climates on the planet. Data collected from the sea ice zone will be particularly important for understanding interactions between cryosphere and atmosphere, ozone chemistry, air-sea flux changes. EU-PolarNet and the need for improved coordination are key for opportunistic access. Teleconnections work should likely consider the tropical to polar influence as well as the polar influence on the tropics.	

Highest Priority Infrastructure and Logistics		
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Ships – dedicated voyages, giving year round access to the Southern Ocean, the sea ice zone and the continental coast.	
	2. Integrated traverse and aviation capability.	
	3. Temporary or permanent bases to enable data collection from the West Antarctic Ice Sheet.	
	4. Deployment of drilling capability – particularly for sub-ocean sediment.	
	5. Opportunistic instrumentation on under way vessels and aircraft.	
	By "infrastructure and logistics", the group is referring to Antarctic stations and transportation. Information and Communications Technology infrastructure is covered under "technology". Others/comments/variances from ARC survey results. Nations wishing to build new stations could be encouraged to focus on West Antarctica. Alternatively, given that the area is also a high priority for ice sheet scientists, perhaps a multi-national expedition or station could be established there. Instrumenting under way vessels might be particularly useful for collecting CO_2 data. Drilling of ice cores is seen to be a well-developed activity, with plans already in place. Data availability was also seen as important, but possibly not largest infrastructure requirement	
What are the estimated costs of providing enhanced **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Dedicated voyages are expensive: hundreds of thousands per week. Ships capable of working in sea ice are important: while some new, more capable, vessels are coming into service, the total number of highly-capable icebreakers globally is in slow decline. New ice-capable vessels cost hundreds of millions of dollars.	
	2. Hundreds of thousands to millions of dollars for a one off traverse. Cost changes marginally for repeat traverses.	
	3. New permanent inland stations and/or stations in difficult areas such as the West Antarctic Ice Sheet can cost many 10's of millions of dollars to build and the ongoing operating costs and risks are high. Temporary and/or portable solutions could be much more cost-effective.	
	4. Requires an escort icebreaker if in sea ice zone (possibly more relevant to Arctic), which means a cost of many millions, even tens of millions.	
	5. Range from thousands to hundreds of thousands of dollars to equip aircraft and ships.	
	Comments: China is bringing new capabilities, especially to East Antarctica: a new icebreaker, a new intracontinental aircraft and repeat traverses to Dome A. All of these capabilities could be used to take observations from new areas, including through the positioning of AWS. New German and Australian icebreakers with moon pools and, possibly in the case of Australia, advanced drilling capability, are planned.	
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All questions.	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	Opportunistic voyages provide relatively low cost access which enhances observational networks in the Southern Ocean. Also supporting real time forecasting is of direct benefit to improved efficiency of resources. However, there are key types of observations, particularly for understanding broader processes, which will require dedicated voyages/expeditions.	

Summary and Conclusions	
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Cooperation across scientific disciplinary boundaries will be particularly important for the cost-effectiveness of deployment and scientific efficacy.
	2. The power technology challenge is critical and cross-cutting.
	3. Need to enhance links between atmospheric research, modelling and operational forecasting, for mutual benefit.
	4. Integrated system science is crucial to progress modelling.
	5. Communication between the polar community and national space agencies/ remote sensing community is vital for improved satellite monitoring.
	6. Cooperation among national providers will be key to big science issues and access to remote regions
	7. Past and future data sharing, distribution and standards are important.
	8. Improved monitoring of the climate and weather systems of the Southern Ocean is vital to understand global connections.
	9. Real-time data crucial for some disciplines.
	10. Winter operations key for process level studies.

HORIZON SCAN CLUSTER 2:
Southern Ocean and Sea Ice in a Warming World

ARC Workshop Writing Group Participants

Co-leads: Anna Wåhlin & John Hall
Stephen F. Ackley, Lautaro Jimenez Corbalan, Chen Danhong, Alexander Klepikov, Joohan Lee, Mariano Memolli, Miguel A. Ojeda Cárdenes, Simon Trotter, Gary Wilson (Scribe)

Scientific Questions	The Southern Ocean has crucially important roles in the Earth system. It connects the world's oceans to form a global system of currents that transfers heat and CO_2 from the atmosphere to the deep ocean. Nutrients carried north support a large part of the ocean's food web, and [the sea ice cover provides an important habitat with a high concentration of algal biomass and krill.] The ocean is becoming more acidic as CO_2 dissolves in sea-water, and cold southern waters will be the first to exhibit impacts. How will climate change alter the ocean's ability to absorb heat and CO_2 and to support ocean productivity? Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? How will the biological pump change? Why have the deepest waters of the Southern Ocean become warmer and fresher in the past four decades? [Closely coupled to the ocean and atmosphere, sea ice and its snow cover reflects and filters sun light. The ice and snow cover modulates heat, momentum and gas exchange between the ocean and atmosphere.] Sea-ice formation and melt dictate the salt content of surface waters, affecting their density, [stratification] and freezing point. What factors control Antarctic sea-ice seasonality, distribution and volume? We need to know. [The ice-shelf-ocean system needs to be understood and active processes quantified. The Antarctic Ice Sheet is the largest source of uncertainty in predictions of future sea-level rise. The Antarctic ice sheet loses mass at the coast from iceberg calving but a significant part is also lost from melting at the base of its coastal floating glaciers (ice shelves). This basal melt is caused by warm ocean currents circulating below the ice shelves and accessing the glacier underside. Ocean warming thus plays a primary role in determining the future behavior of the Antarctic Ice Sheet. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean? What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice and how has it changed historically? How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing? How will changes in freshwater inputs alter ocean circulation and ecosystem processes? How did the Antarctic cryosphere and the Southern Ocean contribute to glacial-interglacial cycles? These questions need to be addressed in order to improve future sea level predictions and other consequences of a changing glacier influx to the Southern Ocean.] – Modified from Kennicutt et al, 2014 (*Nature*)	
Highest Priority Technological Advances		
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Underwater (and under floating ice) navigation and positioning.	
	2. Bandwidth and continuity of data communication from remote locations (specifically underwater including under ice).	
	3. AUVs, gliders and UAVs with greater range (6000 km or more) and capacity.	
	4. Long-term ice and deep-water capable sensor platforms and networks of platforms (including ice tethered platform/profilers, sea ice buoys, drifters, moorings and observatories).	
	5. Unmanned physical and biological sensors and groups of sensors (power needs/ greater efficiency).	
	Comments: • Fit-for-purpose satellite and UAV sensor and capability development (e.g. sea ice thickness) • Development of improved instrumentation for deployment on marine mammals • Using biological indicators as proxy for large-scale shifts in ocean and atmosphere dynamics (scientific challenge but it would help solve the technological challenges of measuring and tracking the marine environment) – e.g. genomics –see the life on the precipice group report. • Sediment cores – see the solid Earth group report.	

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Partially exists – not widely available, range limited. 3-9 years to develop fully.	H
	2. Technology exists – but not for appropriate bandwidth and range needs – additional challenge is applicability to the Antarctic setting. 3-9 years to develop fully.	H
	3. Technology is partially in development, greater range of sensors and power capability is yet to be developed – additional challenge is applicability to the Antarctic setting. Communication challenge yet to be solved. Development is ongoing.	H
	4. Technology partially exists but not readily available and only partly adapted for the Antarctic setting. Long term challenge yet to be solved. Development is ongoing.	H
	5. Some technology available but not in a comprehensive way. Much work yet to be done on biological sensors. Still a power and communication challenge. >10 years to develop fully for biology, less for physical observatories.	M
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	1. Continuously & long term	H
	2. Continuously & long term	H
	3. Measuring continuously but deployed monthly over a long term	H
	4. Measuring continuously but deployed seasonally or annually over a long term	H
	5. Range between continuous and annual for the long term	H
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. $1-10 million USD	L
	2. >$10 million USD	L
	3. $1-10 million USD	M
	4. $1-10million USD	M
	5. No estimate	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/ which questions (by Horizon Scan number)?	Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31, Comment: Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	The communication challenge will require all national programs to work together. The network of coverage and range of environments to be studied will need collaboration of multiple programs. Links to commercial and military entities will be helpful for technological development and technological availability.	
Are there **technologies** and/ or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	No for the top 5 but yes for some of the others – e.g. genomics, continuous. No for deep sediment sampling.	

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	An overarching goal is to move towards much greater automation of measurements and lessening the dependency on ice breakers to perform field work. Several of the technological improvements to move towards greater automation are common between the various platforms (e.g. AUVs, gliders, UAVs, ROVs, floats, drifters, etc) and also common to several other groups. For example, underwater (and under ice) navigation and positioning is needed in order to access the under ice environment. Developments in this field are underway and prototype stage technology exists, but it needs to be made more accurate, longer range, and more available. A community-driven strategy for development in this area is presently coordinated by SOOS. The next over-arching technology that needs to be developed is bandwidth and transfer of large data quantities from Antarctica, including for the marine realm the challenge of transmitting through the ocean itself. Presently this can be done with cable, with sound (limited bandwidth), or through the release of data capsules to the surface. A common and affordable technology for all science fields to transfer data from Antarctica via satellite or high-altitude UAVs is a priority development. The goal of much greater automation of measurements will be limited by bandwidth. Moving towards greater automation will also require better power supplies. Presently technology such as AUVs, UAVs and gliders are limited in range by the power supply. Developing smaller and more powerful batteries, alongside making sensors smaller, cheaper, less power consuming and more modular will make it possible for a new generation of long-range AUVs, UAVs, gliders and animal-borne sensors for the Southern Ocean, its sea ice cover and the under-ice shelf environment. Also and in an effort to move towards greater automation and less dependency on ice breakers is the need to develop long-term networks of buoys, moorings, ice-tethered platforms (including ice buoys) and drifters. Current moorings can be left at sea for about 2 years. In the future at least 5 years duration at sea will be needed. This requires developing the power supply and making long-term stable sensors. Drifter networks do presently exist but they need to be developed for under-ice environment (i.e. the navigation/position capability), for deep sea environments (larger pumps), and for shallow environments. Ice-tethered platforms (including ice mass balance buoys) need to be of longer duration. Unmanned observatories can act as hubs where a multitude of observations (weather station, ice radar, ocean measurements cabled up from moorings, gliders/AUVs, UAVs or buoy networks) are powered and data collected and transmitted via satellite link external to Antarctica. Satellite measurements were discussed and it was agreed that they are very important, and provide perhaps the only presently existing long-term measurements in the area. However, it was also recognized that they need to be ground-truthed, and that there will always be a need for complementary data being collected, e.g., at better resolution or of properties of the interior medium like below the ocean surface and below snow layers on sea ice. Presently the only way to obtain winter-time data of the surface waters of Antarctica is through instrumented mammals. The technology for this exists, although it needs to be made more widely available (i.e., less expensive). The questions about paleoclimate, and extreme events, need to be addressed by studying the deep sediment record presently only available with core drilling, which is a technology that exists but is not yet readily available for use in Antarctica. Studying biology as a proxy for physical properties is an alternative to technology that needs to be better explored and exploited both for present and past climatic settings.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access** ?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Winter / year-round access to the continental margin / shelf edge including important polynyas.	H
	2. Beneath floating ice (sea ice and ice shelves).	H
	3. Circum-Antarctic coverage (specific problems for specific regions).	H
	4. Deep-water.	H
	5. Year-round nearshore access.	M
	Comments: Current areas of high interest include the Ross Sea sector, West Antarctic, Prydz Bay, the Totten and Mertz Glacier regions of East Antarctica, Amundsen Sea, Weddell Sea Sector, and Islands. Marine environmental management, while a scientific need, will potentially drive specific areas of interest.	
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. >$100million USD – requires ice breaker availability and glider/AUV development.	H
	2. $1-10million USD – glider/AUV navigation and hot-water access for mooring network – support from traverse.	M
	3. Mostly better use of existing access networks (e.g. ship track planning, island and coastal stations).	M
	4. Development of autonomous capability/capacity and better use of existing access networks (e.g. ship track planning, island and coastal stations) – $1-10 million USD.	H
	5. Relatively inexpensive where existing stations are available (<$1 million USD), requires significant infrastructure investment where not available ($1-10 million USD).	M
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31, **Comment:** Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements).	

<table>
<tr><td>Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be access ed to accomplish the science of this cluster.</td><td colspan="2">The most significant access challenge for measuring the Antarctic and Southern Ocean is year round access and in particular winter access. Circum Antarctic coverage is also desirable to generate a more comprehensive understanding of ocean-sea ice-atmosphere interaction processes and interaction with the ice sheet and the sub-sea geological substrate. There are areas of current interest and focus, particularly the large embayments fringed by floating ice shelves. Technologically this presents a conundrum as winter access requires a move to more expensive research capable ice breakers but this may come at the cost of wider temporal and spatial coverage of measurements. Some of this challenge may be addressed by autonomous underwater and airborne vehicles but this may drive more specialized and exclusive measurements types at the expense of broader platforms for a range of scientific and technological challenges.

Other access priorities are to develop greater understanding of oceanic and linked cryospheric processes and links to global and biological systems including deep sea and near-shore Antarctic access. The cost of obtaining this access varies – where proximal to existing stations and ship tracks, the cost may be as simple as negotiating better collaboration between national programs. However, there is a challenge to access environments and regions beyond the reach of traditional Antarctic stations and the requirements to access those may range from development of remote observation technologies to unmanned observatories to new temporary research stations.

Consideration also needs to be given to accessing continuous deep sediment records from beneath a range of Antarctic marine environments; to carry out extensive bathymetric mapping at high resolution.</td></tr>
<tr><td colspan="3">Highest Priority Infrastructure and Logistics</td></tr>
<tr><td rowspan="6">What are the highest priority enhancements in infrastructure and logistical support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?</td><td>Rank Order (1 is highest priority)</td><td>Confidence (H,M, L)</td></tr>
<tr><td>1. Greater continuity, coordination, and year round access of research capable ice-breaker(s) – requires international collaboration.</td><td>H</td></tr>
<tr><td>2. Marine and sea ice observatories in high science priority areas (e.g. Islands, Amundsen Sea, Western Weddell Sea, Bellingshausen Sea, and the Eastern Ross Sea) making appropriate measurements.</td><td>H</td></tr>
<tr><td>3. Data infrastructure (data sharing and data management systems).</td><td>H</td></tr>
<tr><td>4. Underwater docking ports to support AUVs, gliders, and moorings.</td><td>H</td></tr>
<tr><td>5. Improved co-ordination of bathymetric data collection.</td><td>H</td></tr>
<tr><td rowspan="5">What are the estimated costs of providing enhanced infrastructure and logistics support needed to accomplish the scientific objectives of this cluster?</td><td>1. >$100 million USD for year round access – better coordination of current access.</td><td>H</td></tr>
<tr><td>2. $10-100 million USD.</td><td>M/L</td></tr>
<tr><td>3. $1-10 million USD – most cost is in the infrastructure development rather than managing the sharing.</td><td>H/M</td></tr>
<tr><td>4. $1-10 million USD ~$1 million USD each.</td><td>M</td></tr>
<tr><td>5. No cost – just agreement to collaborate and work together, perhaps small marginal cost for taking slightly longer ship tracks.</td><td>H</td></tr>
<tr><td>If available, will these infrastructure and logistical needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).</td><td colspan="2">Yes – (Q6 for ocean), (Q7 for ocean), Q12, Q13, Q14, Q15, Q17, (Q18), (Q19 for ocean), Q22, Q23, Q30, Q31.

Comment: Q20, Q21 & 45 require deep sediment cores (not included in the top 5 but included in the other unranked technological requirements.</td></tr>
<tr><td>Provide a short (<500 words) narrative summarizing your conclusions about the highest priority infrastructure and logistical needs to accomplish the science of this cluster.</td><td colspan="2">An overarching goal is to move towards much greater automation and thus in the process reduce infrastructure footprint. However, the most significant access challenge is year-round access and in particular winter access to scientific priority areas that are not currently monitored and observed on a regular basis. In order to achieve the Circum-Antarctic coverage for scientific observation and data collection new observatories (manned or unmanned) will need to be established in high priority coastal areas that currently do not have observatories. There is also an opportunity through international collaboration to encourage existing coastal stations that do not undertake nearshore marine observations to consider doing so in the future.

It is also recognized that there is still an ongoing requirement for better, more focused and coordinated year-round access by research capable ice-breakers.

In order to extend the range and utilization of UAVs, gliders and moorings underwater docking ports could be explored & developed. Such docking stations could enable data download and power provision. Linked to shore stations and or fixed moorings such facilities could transfer data via satellite link.

Some of the infrastructure & logistics challenges are already being addressed by international collaboration but there is an ever increasing requirement to improve such collaboration and integration. Improved coordination and collection of bathymetric data with more effective targeted campaigns is the only way to fill major gaps in the bathymetric data, needed for accurate models of the Southern Ocean. Likewise more effective sharing, management and transfer of data is a major requirement now and into the future.</td></tr>
</table>

Summary and Conclusions	
What are the top 10 “take home messages” from your discussion, i.e., the “big issues” including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Access beneath floating ice (sea ice and ice shelves) is emerging as a common goal to solve a wide range of science priorities.
	2. Greater automation – e.g. AUVs and gliders with greater range and unmanned biological and physical sensors/observatories.
	3. Underwater (and under floating ice) navigation and positioning and communication including docking station development.
	4. Ship access is a significant requirement that will need greater international collaboration. Greater continuity, coordination, and year round access of research capable ice-breaker(s) is needed. Icebreaker instrumentation and its coordination and standardization is also a consideration. .
	5. Long term Ice and deep-water capable buoy networks (including ice tethered platform/profilers, sea ice buoys, drifters and moorings).
	6. Need for new sensor technology (at all levels from in-situ to satellite).
	7. The challenge of big data – data bandwidth and transfer rates including underwater transfer.
	8. Greater collaboration is needed with external agencies (e.g. commercial and other governmental organizations) to help develop and apply new technologies and solve the communication and data transfer challenge.
	9. Many of the groups identified similar access requirements to high science priority areas – e.g. Antarctic embayments (with floating ice shelves & sea ice), Islands and less explored regions. There is also a requirement for access from the deep ocean and across the shelf to nearshore environments including ice shelf cavities.
	10. The challenge of mismatch between position of stations and locations being considered for future science measurements/experiments/observations – solutions will come from multiple approaches, e.g. greater automation, the development of modular and relocatable systems/facilities, new temporary stations and greater interoperability.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	Increasing availability, miniaturization, and modularization of technology. Increasing access to satellite derived data.
Additional comments	International collaboration and diversity of approach is going to be essential to increasing measurement coverage and resolution. The opportunity to develop proposals and gain science funding jointly between international partners would be extremely helpful in developing the collaborations and sharing resources. While the role of modeling in achieving the science goals is understood, considerations were focused on the technological developments, access and infrastructural and logistical needs in Antarctica. While satellite developments were only peripherally considered, the need for inclusion was recognized to address southern ocean and sea ice challenges in the Antarctic. Satellite based methodological development is underway and a greater need for routine data collection and ground-truthing to support satellite coverage and interpretation was deemed important. There are also opportunities for cooperation with the dynamic earth and the atmosphere group and crosscutting solutions are important from paleoclimatic and paleoceanographic approaches – especially horizon scan questions Q20, Q21 & 45.

HORIZON SCAN CLUSTER 3:
Antarctic Ice Sheet and Sea Level

ARC Workshop Writing Group Participants

Co-leads: Sridhar Anandakrishnan & Martin J. Siegert
Sun Bo, Don Blankenship, Lorna Little (Scribe), Heinrich Miller, Uwe Nixdorf (Scribe), Hernán E. Sala, David G. Vaughan
Jan-Gunnar Winther

<table>
<tr><td>Scientific Questions</td><td>"The Antarctic ice sheet contains about 26.5 million cubic kilometers of ice, enough to raise global sea levels by 60 meters if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO_2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown." Kennicutt et al., 2014 Nature COMMENT</td></tr>
<tr><td colspan="2">Highest Priority Technological Advances</td></tr>
<tr><td></td><td>Rank Order (1 is highest priority)</td></tr>
<tr><td rowspan="9">What are the highest priority technological needs to answer questions in this cluster?</td><td>1. Process driven numerical ice sheet modelling

Various aspects of modelling need to be developed, including better accounting for:
a. bed topography and characteristics (needed as a vital model input),
b. surface mass balance (needed as a vital model input)
c. basal conditions (to avoid current situation where they are calculated internally with little attempt to link with real data),
d. ice structure, fabric and anisotropy (see #2), presently unaccounted for, with no attempt to link with data (layers, polarimetric radar etc.),
e. ice and geothermal temperatures,
f. basal hydrology,
g. distribution of basal sediments,
h. 3-D flow of ice (little if any link with internal layering),
i. grounding lines/zones,
j. Ice shelf modelling and iceberg calving with coupling between ice/water/atmosphere, and
k. lithospheric treatment (GIA)

Limitations in ice sheet modelling is a major aspect of the uncertainty in predicting and understanding ice sheet change and sea level rise. Model development needs continued coupling between the glaciological modelling and observation communities.</td></tr>
<tr><td>2. Subglacial sampling – where short-term (on the order of days) rapid, reliable, clean access is required, sampling at or near the ice-bed interface.</td></tr>
<tr><td>3. Combined multiple geophysical measurement and sampling of ice. Ice fabric development and its rheological implications. To understand numerous subsurface properties from measurements conducted at the surface including deep ice core and paleoclimate record recovery.</td></tr>
<tr><td>4. Satellites making synoptic, operational measurements of snow and ice accumulation. Needed in conjunction with targeted field observations, including SMB and GIA, to yield accurate surface mass balance fields.</td></tr>
<tr><td>5. Autonomous sensors remotely deployed and remotely accessed, acquiring information on ice shelf bathymetry and ocean conditions. For example, grounding zones.</td></tr>
<tr><td>6. Subglacial sediment recovery. Where deep core material is collected, requiring long-term access to the bed (on the order of weeks).</td></tr>
<tr><td>7. Greater use of AUVs (autonomous unmanned vehicles – submersible). AUVs campaigns can be guided by airborne gravity and seismic data to map ice shelf bathymetry in detail in key regions. Oceanographic time series measurements of water temperature, currents, salinity, turbidity, etc. under the ice shelf.</td></tr>
<tr><td>8. UAVs (airborne) with geophysics, including Swath radar allowing 2-D mapping of ice sheet bed and conditions.</td></tr>
<tr><td>Comments: Open data policies, perhaps also push for open technology policies. Open discussions between engineers, technologists and scientists through international collaborations.</td></tr>
</table>

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1.	The major limiter for ice sheet modelling is the lack of observations, both for model input and to understand ice sheet processes not adequately modelled at present. For ice sheet fabrics no models exist due to the lack of field data; for bed conditions, ice sheet models perform poorly due to scarcity of measurements; for ice shelf processes, calving laws and ice-ocean interaction is poorly known. For ice and bed temperatures: models do exist, just not applied regularly due to computational cost. Lack of observations are holding model development back. Next generation of models are needed, and ice sheet modelling needs to be scaled up, along the lines of global climate modelling. Modelers must integrate with observational glaciology. Substantial improvements in numerical ice sheet modelling are needed.
	2.	Subglacial sampling at (or near to) the bed – technology does exist, but not widely available. Not for regular measurements, but cleanly, at certain depths (currently ~800m). Access at greater depths (e.g. RAID) allows access to the frozen bed but is not (yet) clean. 5-10 years to achieve clean sampling to greater (~3km) ice depths.
	3.	While multiple geophysical techniques have been deployed in Antarctica, they have seldom been used collectively in a targeted manner, due to operational and logistic limitations. Technological advances in geophysics, (e.g. reducing the need for wires, mobile seismic sources, polarimetric radar) are now available for this purpose. 5 years to perform a showcase exercise, demonstrating the utility and feasibility of the approach.
	4.	Snow accumulation data from a satellite – 10 – 20 years, doesn't exist at present.
	5.	Remotely deployed instruments (for challenging regions, e.g. grounding zones) – technology exists, 5 – 10 years away, not widely available, need higher resolution technologies.
	6.	Subglacial deep sediment recovery – some technology exists (e.g. ANDRILL), but not widely available and never tried on ice sheets. 5 – 10+ years.
	7.	AUVs underwater, to measure ice shelf cavities. Technology exists, some development still needed 5-10 yrs. away.
	8.	UAVs airborne. Ice sheet topography/basal conditions. Technology exists, some development still needed 5-10 yrs. away.
		Comments: In 20 years these technologies need to be routinely deployable. Open data policies will be needed to allow processing of the 'big data' created.
At what temporal scales will these **technologies** most likely be used and how frequently?	1.	Ice sheet modelling – not applicable to this question.
	2.	Subglacial sampling – dependent on access, technology and cleanliness protocol. A small number/year.
	3.	Geophysical measurement and sampling. A small number/year.
	4.	Snow accumulation from satellites – at least 30 day repeat or better, for multiple years. Potential big data implications.
	5.	Remotely deployed and operated sensors (e.g., grounding zones) – types of measurements vary, short term use (max 2yrs), sending real time information every few minutes. Potential big data implications.
	6.	Subglacial sediment recovery – dependent on access, small number/year – but has to be done within a season.
	7.	Underwater AUVs (for ice shelves) – seasonally, potentially year round.
	8.	Airborne UAVs (for ice sheet geophysics) – potentially all year round.
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1.	Modelling – $10+ million USD to set up comprehensive system.
	2.	Subglacial sampling – ~$10+ million USD.
	3.	Combined multiple geophysical measurement and sampling of ice – ~$10 million USD.
	4.	Satellite – ~ 150 – 300 million USD, plus launch costs.
	5.	Autonomous sensors – technologically money to be invested in development ($1-5 million USD), once available there will be a significant savings in production.
	6.	Sub glacial sediment recovery – dependent on sampling target. $1 – 10 million USD, depending on target.
	7.	AUVs – similar to sensors, multi million for development, but scaling down once developed. Key is robustness for deep diving. $5 – 10 million USD.
	8.	Airborne UAVs – 5 million USD to equip UAV with full geophysics suite. $5 – 20 million USD. Smaller ones are $1M to develop, $100,000 USD to fly. The price depends on the platform and scale – small cameras on a remote controlled UAV up to Global Hawk at $20 million USD.

Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	1. Ice sheet modelling – 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 2. Subglacial sampling – 25, 26, 27, 32 3. Combined geophysical measurements and sampling – 24, 25, 26, 27, 28, 29 4. Satellite – 25, 29, 31 5. Autonomous sensors – 24, 25, 26, 27, 29, 30 6. Sub glacial sediment recovery – 25, 27, 32, 33, 34 7. AUVs (water) – 24, 25, 26, 28, 30, 31 8. UAVs (airborne) 24, 25, 26, 27, 28, 29, 30, 31 Also, relevant to Qs in other sections, such as 7, 8, 38 and 40.
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Outside of NAP: Satellites, AUVs and UAVs. Subglacial access won't be used for anything else, so within NAP capabilities. Instruments on and platform for AUVs and UAVs are probably beyond an NAP. All these technologies could be deployed in Greenland. Global ocean and climate modelling will not be completed by NAP, but it is essential for Antarctic models. Development of coupling of ice model to any of the global models needs collaboration between international institutes.
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Yes. Widely accessible high band width communications. If UAV or AUV could pop up and link in, that would be transformative. A Sub orbital (non-satellite) system is needed. Such data communications and networks exist outside of the Antarctic. For example, a sequence of balloons could provide bandwidth on the ice – and is being done in South America right now. Arctic Council recently established task force to investigate communication satellite development – Antarctic community could have some advantage of that in future. Power management systems (fuel cells, batteries, flex solar panels, wind generators) for remote observatories/stations. All this is low tech and available, but not enough for purposes required (batteries don't last long enough etc). Miniaturization of Automated Weather Systems and GPS technologies. High cost due to small market, need to advertise outside of Antarctic to increase market and decrease cost. Automated Weather Systems and GPS already as small as they can go. Batteries still need development. There are people who work solely in miniaturization who do not work in Antarctica. If they did, that could be transformative. Wireless Geophones; 3-D seismics. Exists now, could be imported from exploration industry.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	Understanding Antarctic ice sheet and sea level change requires ice sheet modelling for predictions, making such modelling a key priority in this section. Ice sheet models have improved considerably over the past 20 years, but substantial improvements are needed to better constrain predictions and reduce uncertainty. Such improvements are mostly constrained by lack of knowledge/observation relating to key processes, underlining the need for modelling and field data acquisition to be coupled. High confidence that ice sheet modelling is capable of describing the real flow of ice in Antarctica, including all relevant processes, and that this can be achieved over a 20 year timescale. While ice sheet modelling is a priority, these other items are not prioritized in order. a. Knowledge of ice and snow accumulation rates is poor and requires satellite measurements to make the advance in observations necessary. b. Ice sheet flow is affected by basal processes and ice rheology, both of which are not well described in models. To obtain the necessary observations, sampling of the subglacial environment and englacial environments are needed. To guide sampling, geophysical imaging of the ice sheet is needed. c. Critical regions of the ice sheet, such as grounding zones and shear margins, are challenging for deployment of personnel. Solutions here involve the use of remotely deployed expendable instruments. d. Also critical to ice sheet change are ice shelf and grounding zone processes, requiring both on ice and sub-ice shelf measurements. The interface with oceanography being important here. e. Knowledge of past ice sheet changes require samples of ice and basal sediment, guided by improved geophysical measurements. f. Potential exists to use unmanned aircraft to expand geophysical data coverage. Also, industry standard 3-D seismics could offer transformative insights into basal processes and ice structures. g. Miniaturization of equipment, undertaken in other areas of science (e.g. space science) could be used well for Antarctic purposes, offering important savings on weight and power, and extending the time series of measurements. h. All of the technological advances discussed above are pertinent to more than one of the Horizon Scan questions in this section. Some of them, ice modelling and geophysical measurements, and ice/sediment sampling, are relevant to most of the questions. Others, underwater vehicles are linked strongly to oceanography use and, hence, the oceans section. i. Finally, with the enhanced communications being used regularly in other geographical regions, and with the coming 'big data' from instruments (in real time and enhanced resolution), sub orbital communications networks are seen as an important step for the next generation of ice-sheet measurements.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access** ?	**Rank Order (1 is highest priority)**
	1. Amundsen Sea Embayment, basin. Thwaites Glacier System, West Antarctic.
	2. Deep marine margin-interior of ice sheets, including grounding zones.
	3. Deep interior Antarctic Plateau.
	4. Coastal islands and ice rises. Obtaining paleoclimate from coastal regions, and deep time from the interior. Blue ice – Including horizontal ice coring.
	5. Sedimentary basins, for their value in obtaining process information and sedimentary records.
	6. Ice shelf cavities/systems.
	7. Shear margins – records of ice sheet change within the system.
	Comments: Geographical regions were identified as being important as a consequence of observed changes. We are unable to predict in twenty year time period which other regions may experience change and therefore it is necessary and wise to obtain measurements in places potentially vulnerable.
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Thwaites Glacier – could do a lot for $20 million USD per year, over 5 years. $100 million USD.
	2. Marine portions >$–10 million USD per year per geographical region e.g., Wilkes, Totten
	3. Interior ice – $60 million USD.
	4. Ice rises, coastal – approx. $2 million USD, but it is dependent on proximity to existing facilities.
	5. Sedimentary basins >$10 million USD.
	6. Ice shelf cavities/systems $5 – 10 million USD per cavity.
	7. Shear margins – depends on how adventurous one wishes to be. Autonomous network ideal – $1-2 million USD.

If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	1. Thwaites – 24, 25, 26, 27, 28, 29. 30, 31, 32, 33, 34 2. Marine ice sheets – 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 3. Interior ice – 24, 25, 26, 27, 28, 32, 33, 34 4. Ice rises, coastal ice – 24, 25, 27, 28, 29, 30, 31, 32, 33, 34 5. Sedimentary basins – 24, 25, 26, 27, 32, 33, 34 6. Ice shelf cavities/systems – 24, 25, 26, 28, 29, 30, 31, 34 7. Shear margins – 24, 25, 26, 27, 28, 32, 33
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access** ed to accomplish the science of this cluster.	The highest priority is access to regions of the Antarctic that are either currently contributing significantly to sea level rise, or will likely do so in the century to few-century time scale. Glaciological models and theories identify marine ice sheets (those parts of the ice that are grounded below sea level) and the grounding zones fronting those ice sheets as the most vulnerable to rapid and irreversible change. Thwaites Glacier and its surrounding grounded ice and glaciers, ice-shelves, and the Amundsen Sea are currently undergoing rapid change and are identified as the highest access priority. In order to study the system, extended-season access is needed to the ocean and ice-shelf environments; access to the difficult grounding zone is necessary; extended-season access to the interior for geophysical, drilling, and sampling work is needed. Though Thwaites Glacier is currently undergoing change, there are numerous marine ice-sheet basins in East and West Antarctica that may do so in the future. Measuring, modeling, and monitoring these as baselines for their current configuration, and for better assessment of their eventual rate of contribution to sea level is needed. Access to these basins (Wilkes, Totten, Amery, Getz etc.) is a high priority. These marine ice sheets are linked to the internal reservoir of the full Antarctic Ice Sheet, and understanding the full contribution to sea level requires access to the interior. The distribution of subglacial sedimentary basins and the properties of those basins has an influence on the flow of the ice sheet and of the ability of the ice sheet to stabilize against perturbations from, e.g., ice shelf or grounding line changes. In addition, sedimentary basins contain a record of past changes that can improve understanding of the response of the ice to well-known climate forcing. The stability and configuration of ice shelves that fringe marine ice sheets are one important control on the contribution of that ice to sea level change. Understanding ice shelves and the adjacent grounding lines requires access to a complex and dynamic region of sea-ice and icebergs on the one hand and crevasses on the other. Access to this part of the system is critical and will require technological innovation and significant logistic effort. In similar manner, lateral shear margins of glaciers (which separate rapidly flowing ice from slow-flowing ice) are poorly understood features of the ice sheet. They are difficult to access because of crevasses, but technologies similar to those proposed for grounding zones and ice shelves could be used here.
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	1. Lengthen operation window for field work. Doubling length of season could double progress of science, not amount. 2. Mobile and temporary stations. Fixed assets could be less than optimal due to changes in science direction based on observations and modelling. Need stations that are deployable into difficult areas, and moveable. Should be achievable on 20 year scale, e.g. high priority Thwaites Glacier. Similarly, developing inland/plateau traverses – especially with electrical tractors and sledges which hold the buildings, will maximize trans-Antarctic science. 3. Fuel efficiency. More efficient deployment of fuel AS WELL AS alternative/renewable energy sources. Innovations in solar panels and power systems for large bases. 4. Communications – sub orbital network. 5. Stronger, recognized and organized framework for transnational collaboration and logistic uses (e.g., perhaps similar to SIOS, INTERACT). Need to find right mechanisms and still keep domestic priorities, maybe by pooling of national resources. Polarstern example is optimal. Increase international cooperation and support for logistics. 6. Multilateral research council co-funding agreements.
What are the estimated costs of providing enhanced **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Mobile stations – 10+ million USD (capital investment) 2. Fuel efficiency measures and renewable sources saves money 3. Communications – see earlier estimate 4. Recognized international network of logistics – doesn't have a cost, just do it 5. Research council co funding agreements – doesn't have a cost but will likely be met with resistance. Can only happen with multilateral scientific imperatives, which individual nations cannot achieve on their own. 6. Field season – cost of achieving this can't be estimated, but the likelihood is it will produce efficiencies/savings long term

If available, will these infrastructure and logistical needs support multiple scientific questions in this cluster?	1. Field season length 2. Mobile stations 3. Fuel efficiency 4. Communications 5. Recognized logistics network 6. Research council co funding All apply universally to the research questions in this section
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	The contribution of Antarctic ice sheet to future sea-level rise, is an issue with immediate and global significance, with impacts to lives and livelihoods in coastal communities and economies around the world. The urgency surrounding these issues, will be reflected in the requirements placed on logistics and budget support in Antarctica. The development of an optimal logistical capability to support rapid progress in ice sheets and sea-level research will require attention to technological advances, planning of key infrastructure and a removal of barriers, to multidisciplinary science, to effective international and inter-agency collaboration, the cooperative development of science strategies, in the joint/cooperative allocation of funding, and crucially in sharing of logistics support. Many recent advances have been achieved through satellite and airborne remote sensing, and an ongoing capacity is a prerequisite for rapid progress in this field; ensuring this capability cannot be overlooked as a task for polar science. In the last decade, rapid advances in observation and modelling have created high-priority targets for research, which are both geographically glaciologically specific. These will persist for at least another decade, but over the coming 20 years it is likely that other priorities will arise, and this expectation demands flexibility in logistic capability and planning. In many areas, technologies that are developed for one-off experimental campaigns will be required to achieve, an operational status, either deployed to multiple sites or established as long-term monitoring stations. Such sampling is needed over wide geographic areas, and over periods of many years in order to provide the density of sampling required to inform ice-sheet projections. Much of the work needed to support ice-sheet modelling will continue to be remote from permanent stations, and this will need to be supported by mobile and remote field-parties, and through remotely operated sensors and rovers. The efficiency of these parties (rapidity, scale and duration of deployments) should be improved (e.g., through appropriate cold-hardening, and deployment/support options). Innovation in the logistic technology available to support of field activities, through flexible, and rapidly deployable facilities (e.g. traverse parties, field camps, moveable stations) may require cooperative development.
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return? ** T= Technical Issue ** L = Logistical Issue	1. Modelling coupled with observations; next generation ice sheet model, capable of describing the real flow of ice, linked with ESS models. Predicting change is the goal. Bed topography, fabric, heat flux, sediments, temperature, etc. (T)
	2. Access to interior Amundsen Sea embayment ice sheet, ice shelf and grounding zone, to make the observations needed to drive models. (L, T)
	3. Recovering datable subglacial material revealing details on the last deglaciation of all, or part of, West Antarctica. (L)
	4. Comprehending palaeoclimate signal from the basal layers (thinned and sometimes disturbed ice). Requires rigorous high resolution site selection geophysics and modeling and detailed analysis of ice-core material. (T, L)
	5. Characterizing Antarctic ice shelf cavities, from grounding zone to continental shelf systems (including subglacial discharge, iceberg production, transport and melt), around the continent. (T, L)
	6. Real time remote data recovery (in challenging locations, e.g. grounding zones and shear margins). (T)
	7. Understanding the spatial/temporal evolution of subglacial water systems, and the consequences for ice flow. (T)
	8. Ability to rapidly deploy to potentially changing regions, e.g. deep subglacial marine basins, with benchmark knowledge to constrain changes. (L)
	9. Comprehensive surface mass balance measurements. (T, L)
	10. Knowing the flow of ice in vertical profile in all places from interior to grounding zone. (T, L)

Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	a. Miniaturization of sensors. b. UAVs (air). c. AUVs (water). d. Robotics. e. Big data. f. Suborbital communication networks. g. Computational power. h. Inter- and intra-continental facilities – expanded gateways to Antarctica, enhanced landing facilities in Antarctica, and support for distributed science delivery. i. Geophysical techniques. j. Continuity and further technology development in satellite remote sensing of Polar Regions.

HORIZON SCAN CLUSTER 4:

Dynamic Earth – Probing Beneath Antarctic Ice

ARC Workshop Writing Group Participants

Lead: Carlota Escutia
Juan Jose Dañobeitia, Jane Francis, John E. Guldahl, Yeadong Kim, Yoichi Motoyoshi, Jeronimo López-Martinez, Xu Shije, Kazuyuki Shiraishi, Brian Stone, Terry Wilson (Scribe)

Scientific Questions	*"Reveal Antarctica's history. Glimpses of the past from rock records collected around the continent's margins suggest that Antarctica might look markedly different in a warmer world. But rocks from the heart of the continent and the surrounding oceans have been only sparsely probed. Responses of the crust to, and the effects of volcanism and heat from Earth's interior on, overlying ice are largely undescribed. We know little about the structure of the Antarctic crust and mantle and how it influenced the creation and break-up of super-continents. Ancient landscapes beneath ice reveal the history of interactions between ice and the solid Earth. Geological signatures of past relative sea level will show when and where planetary ice has been gained or lost. We need more ice, rock and sediment records to know whether past climate states are fated to be repeated."* Kennicutt et al., 2014 *Nature* COMMENT
Highest Priority Technological Advances	
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**
	1. Sensor arrays **1A. Remote sensors/off continent sensors:** not done on site in Antarctica (satellites) Satellite-hyperspectral for example. Resolution limits application **1B. Remotely-deployed sensors** – deployed in Antarctica/Southern Ocean. People do not need to be on site (except for deployment, retrieval, and/or multi-year maintenance cycles). Examples: Geodetic, geophysical (Weather stations, GPS, broadband seismic, magnetic, etc.) **1C. Field surveys** (*airborne, land, marine*) a. Airborne (radar, altimetry, geophysical) b. Field sampling and *in situ* analysis – miniaturization of analytical instruments (application of Mars Rover-style instrumentation) c. In future, could aid in effective sampling, on-site decisions of how much/where to sample. d. Aircraft, helicopters, AUVs (Autonomous underwater vehicles); ROVs (Remotely operated vehicles); UAVs Unmanned aerial vehicles. Payloads. e. Robotics in collection of meteorite sample on ice sheets **Comments on Sensors:** a. Technology developments for sustainable, long-term data transfer sensors b. Standarization of sensors c. Connectivity and interoperability of sensors d. Multi-sensor networks may be required for science, but *will* be required for efficiency of resource use (funds, logistics) **Comments on Resolution/sample rate:** a. Resolution/Defining data requirements – All science to progress in future will require higher resolution b. Given resolution limits 1A-calibrated by 1C required. c. Different dynamic rates (earth vs ice movement, for example), require different resolution of measurements. d. Discrimination based on sample rate required for the science is essential. Volumes of data to be collected, and potentially to be communicated remotely, is a critical starting point to define technologies required. - Full data transfer? - Triggered data transfer? - Data storage? **Comments on environmental impact:** Environmental impact of 1B and 1C always needs to be assessed – high risk, moderate risk, low risk, of environmental impact of technology to be used. **Comments on Power:** Note of emphasis – to achieve *power* goals including a) new power sources and b) new low-power instrumentation, NEEDS: *Technology transfer from existing systems, e.g. as used in space programs.*

<table>
<tr>
<td rowspan="5">What are the highest priority technological needs to answer questions in this cluster? (Continued)</td>
<td>2. Subglacial access/Downhole borehole sensors (ice, land, marine) for direct measurements – requires drilling and deployment of instruments (short- or long-term). Logging, probes, sensors Into ice, sediment, rock.

Image capture/analysis

Comments: Technology developments: standardization of technology, connectivity and interoperability</td>
</tr>
<tr>
<td>3. Sampling of ice, sediment, rock – drilling to take samples out, including ice coring, and drilling into seafloor and subglacial materials to collect both sediments and bedrock.

Notes on required developments:

a. Development for clean/greener technologies
b. Rapid access drilling technologies
c. Drilling technologies (including riser) for improvement of recovery of marine sediments/rocks (both consolidated and unconsolidated glacigenic sediments)
d. Development of sea bed drills-flexibility

These 2&3 categories cover the list of 2,3,4,5 in the Survey 1 'Top Five' list.</td>
</tr>
<tr>
<td>4. Data Communication Capacity – high volume, long-distance data transfer capabilities for sensor networks, ice, sediment, rock loggers, etc.

Comments: development for faster, reliable, affordable data communications capability</td>
</tr>
<tr>
<td>5. Power

a. New power sources: efficient (high power density), lightweight, environmentally friendly, capable of operating in extreme cold conditions. Develop alternative energy sources.
b. New Instrumentation designed for low power consumption, with efficient power management.</td>
</tr>
<tr>
<td>Comments: The top priorities emerging from the surveys were restated but retained and items raised in the White Papers were added. 'Universal' issues (data communications, power) are emphasized.

Other topics for prioritization considered but not fully discussed:

a. Improved geological models
b. Sample analyses technologies</td>
</tr>
<tr>
<td>What is your estimation of the current status of the highest priority technological needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?</td>
<td>1. Sensor arrays ("signals")

a. Remote sensors/ off continent sensors – Satellites
i. Could influence ongoing prioritization for satellites with polar applications.
ii. Investigate if 'hosted payloads' – sensors with special polar applications – can be added to payload planned for a satellite that will be launched for another purpose. 'Only' add-on cost required.
10+ years' time frame

b. Remotely-deployed sensors – deployed in Antarctica/Southern Ocean. Many remote instruments operational currently; however, development required to achieve sustainable systems for long-term. Cyclical upgrades to take advantage of technological advances (obsolete instruments; lower-power; etc.).
i. Interoperability essential to ensure successful multi-sensor networks and international networks:
ii. Connectivity: A plug-and-play power and communications system that can be used for a variety of sensors.
iii. Standardization – any type of sensor can be plugged in, as science needs evolve. Any nation can contribute to network. Also, data should be aligned so can be used by multiple communities.

3-9 years' time frame

c. Field Surveys
i. Robotics and autonomous vehicles – development required, and dependent on payload requirements, spatial survey requirements
ii. Technologies required to deploy remote instruments in special polar environmental conditions – for example aircraft, helicopters, ROVs and UAVs in sea-ice-covered waters. Technologies are required to manage operation of remote instruments – for example, airborne drones.
iii. Miniaturization of instrumentation for field-based analyses requires development for cold environment operations.
iv. Strategies to prioritize operation of remote sensors vs. field-based surveys. Operations managers face 'either/or' choices – funding insufficient to continually add on (for example, airborne geophysics such as IcePod in addition to other modes of airborne surveys or field-camp-based geophysics). Science community needs to prioritize which is preferred mode of data acquisition to meet science requirements.</td>
</tr>
</table>

	2. Subglacial access/Downhole borehole sensors – This category includes instrumentation requirements applicable to: subglacial lake environments, ice, rock, marine, and land. Many instruments have been deployed but, again, development required to permit sustainable, reliable, environmentally 'clean', etc, operations. Development requirements are dependent on instrumentation requirements, spatial extent of measurements, etc. *2 year time frame*
	3. ***Sampling of ice, sediment, rock*** a. Ice – ice coring technologies… (no expertise in room /check with ice sheet group in cross-cut discussions) b. Subglacial bedrock core recovery requires development: *3-9 year time frame* a. Multi-substrate sampling: ice, then sediment, then bedrock sampling, capacity needed. b. A 'rapid drilling' system required (i.e., development of the RAID system, rotary drill rod systems, wireline rapid drills, etc). *3-9 year time frame* **4. Ocean sediments:** a. Improved recovery technologies for ocean drilling required (riser systems). b. Seabed drilling technologies essential. *2 years* Improved availability of existing technologies (e.g., ANDRILL and IODP) is very important – i.e. science requires more sample records, acquired over shorter time cycles (i.e., not a decade between major core acquisition programs)
	5. *Data Communication Capacity* – A major 'step function', as soon as possible, is required to enable the range of science proposed. Development on many fronts is required: a. increased bandwidth b. increased speed c. reliability d. affordability **Comments:** data can be collected at rates and volumes that can never be transferred by satellite technologies. WHAT needs to be transferred – 'state of health', 'communications to execute project', or actual 'data'? Is there *really* a tight time frame for receiving data, if the analysis is going to take 3 years? Is the data analysis part of a funded project? Or, will the data be collected by one project, but then analyzed by separately funded projects subsequently? Virtual deployments, expanding science community, important. Are there improvements in 'local/regional communication networks' that would improve science projects, science operations? Can there be coordinated transmission of data? Would communications between different operators about operations aid progress of science implementation (for example, King George Island)? What are the scale factors? a. Spatial b. Numbers of instruments (bandwidth) Issues: a. Satellites are not in orbits to service communications in Antarctica b. How do multiple nations share satellites? Are there 'geopolitical issues? Can we support a 'COMNAP satellite'? Also important to consider investment in data management – for example, data compression, or on-site processing and only transfer 'products' not all raw data *3-9 year time frame*

	6. *Power* Development elements required include: a. Affordable b. Greener c. Lighter d. Safer e. Operational low-temperature conditions f. High capacity (high energy density) g. Reliable **a. Power Sources** Develop alternative energy sources *Within 2 years* up to 3-9 year time frame* * requires access to commercial technologies and enhanced cold-environment testing. Mid-size stationary generators are now under development but is still required lighter equipment and advance temperature management and enclosures. **b. Low-power instruments** Important to coordinate between developers, important for engineers to design together with scientists. – *short term, but 3 (not 2) year time frame*
	Comments: Common Issue: technologies exist, but no easy (or any means) for polar science community to access or deploy. Examples: 3D seismic, drilling systems, and data transfer.
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	**1. Sensor arrays ("signals")** a. Remote sensors/ off continent sensors – Satellites – Repeated, any time of the year b. Remotely-deployed sensors – Continuous OR 'any time during the year' c. Field surveys – Austral summer (October-March)
	2. Subglacial access/Downhole borehole sensors a. Multi-substrate sampling / A 'rapid drilling' system required. b. Continuous OR 'any time of the year' c. Ocean sediments: i. Improved recovery technologies for ocean drilling required. ii. Seabed drilling technologies essential. Austral summer (October-March)
	3. Sampling of ice, sediment, rock Austral summer (October-March)
	4. Data Communication Capacity Continuous OR 'any time of the year'
	5. Power – Continuous
	Comment: Continuous is different than 'Any time during the year'
What are the estimated costs to develop/deliver the highest priority **technology** needs? See Survey results for the cost ranges to be used. This is not intended to be a rigorous cost analysis but a general indication of cost to the best of your estimation. If you have no basis for such an estimation please indicate "Don't know", do not guess.	**1A. Sensors 'off continent' – Satellites** $>10,000,000 (25,000,000 – 50,000,000 cost) **1B. Sensor networks – observatories and networks on land or on seafloor:** $1,000,000 – 10,000,000 cost – but this is probably per network, not for an integrated multi-sensor network **1C. Field Surveys**: $1,000,000 – 10,000,000 cost a. Auto-sub: 10million b. IcePod: 3-5 million c. Glider: 0.5 million

	2. Subglacial access (downhole borehole sensors: $500k – 1,000,000 to 1,000,000 – 10,000,000 cost a. temperature probe: <<500k, b. image capture: relatively low cost, c. borehole sensors: mainly relatively low cost?, and d. subglacial lake ROV: 1-10 million
	3. Sampling of ice, sediment, rock: $1,000,000 – 10,000,000 to >10 million cost per project/mission a. Seabed drill (e.g. MeBo): $10 million b. Ship based (IODP): $ 10 million c. Ice shelf based: $10-20 million d. IceCube drill: $25 million e. Rapid Access drill: $~5 million **Comments:** not just purchase cost, but ongoing maintenance costs are commonly the most challenging.
	4. Data Communication Capacity: $500k – 1,000,000 to >10 million cost Satellite for comms: >>10 million
	5. Power – Power sources – $500k – 1,000,000 to 1,000,000 – 10,000,000 cost new battery type: cheap (assuming using off-the-shelf)
	Comments: Considerations on estimated costs: Conceptualize 'support packages' to figure out costs. a. Human, and support chain needed to deploy human, required. b. Technological solution can be substituted. At what point does the investment in B, allow down-sizing to logistical hubs (field camps, stations) with the whole supply chains, which magnifies the cost savings? 'Science' funds vs. 'logistics' vs. 'infrastructure' vs 'technology development' funds – how to actually map all the latter, into the actual science costs?
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	Yes, all questions in the cluster would be addressed
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	a. Power source research efforts will be carried out by commercial interests, national energy departments, etc. Perhaps a consortium of polar programs could commission research on cold-environment-capable energy solutions. b. Planning polar orbit for satellites. Hosting payloads on satellites. c. Low-power instrumentation is of more global interest for science experiments, however, the extreme environment testing is mainly applicable to polar research. d. Drill technologies will need to be developed in collaboration with the commercial drilling sector
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	**Oil industry technologies:** a. 3D seismic b. Drilling: i. Ongoing operations, i.e. not once a decade. Long gaps between projects have meant: 1) a slow progress addressing relevant scientific questions and; 2) that significant technology and capability (especially people) has been lost without adequate training of new capability. ii. Seabed drilling systems **Fiber-optic communications cable to Antarctica** Note; Satellites in polar orbit can download data to Antarctic sites that is then fed to, for example, weather forecasting systems in the northern hemisphere, significantly improving forecast certainties – if these data can be transferred rapidly, for example by fiber-optic cable, could have global impacts – 250 million dollar cost UAV – Unmanned Autonomous Vehicles. Large UAVs, with major long-range spatial capabilities and large payloads, are routinely used outside Antarctica. For example Global Hawk UAV (deployed from off-continent). Nuclear power – future cost-efficient, reliable, environmentally-friendly system developed, then will the political issues allow it to be deployed in Antarctica?

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	The technologies necessary to address the scientific questions in the Dynamic Earth-probing beneath the Antarctic ice´ include: a. Sensor arrays on the continent and in ice/subglacial boreholes; b. Technologies for data and sample collection during field surveys (airborne, autonomous and unmanned and remotely operated vehicles; field sampling, miniaturization, low power requirements, robotics, etc.); c. Drilling systems for the collection and complete recovery of sediment and rock samples from beneath the ice and the ocean. Some of these technologies largely exist, are under development, or require improvements that are achievable in the short-term. Improved availability of existing technologies is key for science advancement, allowing for regular/repeated collection of samples and data. Other needed technologies, such as subglacial bedrock/ sediment core recovery or satellite hosted payloads will require 3-9, or more than 10 years to be developed, respectively. Technological developments should aim for the standardization of sensor technology, and the connectivity and interoperability of sensors. This is essential for to ensure successful multi-sensor networks, and to facilitate international collaboration and interdisciplinary science. In addition, multi-sensor networks will also be important for efficiency of resource use (funds, logistics). The questions in this cluster cannot be fully addressed unless large spatial areas, both in the Antarctic continent and the surrounding oceans, are investigated. Some of the questions in the cluster are best addressed in East Antarctica or West Antarctica target regions, though still broad regional areas. The deployment of sensor arrays and increased science activity in Antarctica with the possibility of acquiring continuous or any-time of the year data and the direct communication with the sensor network, will require improvements in the data communication capacity for high volume, long distance data transfer capabilities. All activities described would benefit from power source improvements including, sources for low-consumption instruments, with efficient power management, and new green, efficient and lightweight power sources that can reliably operate in extreme cold polar conditions. All activities conducted in Antarctica and surrounding oceans will have to be environmentally friendly, and benefit from international interdisciplinary collaboration and coordination of science, logistics and infrastructure. The technological requirements for sensor networks, ice borehole drilling and sampling of subglacial sediment and rock cross-cut with needs/requirements in the ` Antarctic ice sheet and sea level´ cluster (geophysical, AUVs, ROVs, etc. Q.24. Q26-32 and subglacial and ocean drilling Q.34). Paleoclimate records of past greenhouse conditions that are recorded in sub-ice and ocean sediments and rocks are also relevant to the`Antarctic atmosphere and global connections´ cluster (Q.8, Q.9), in addition to the geophysical data, sensors and samples that will allow for a better understanding of the distribution and volumes of greenhouse gases stored on the permafrost and clathrates (Q.10). Samples of sediment and rock will also provide information about ecosystem evolution in Earth history (Q. 46).

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**? See Survey results for location descriptions.	**Rank Order (1 is highest priority)**
	1. On the Antarctic Continent **Priority – Deep interior of continent** East Antarctic interior is a priority for studying supercontinent evolution, West Antarctica is a priority for studying volcanism and impact on ice sheet. Need is to visit interior rock exposures, deploy sensor networks, conduct airborne and other field surveys, exploration of subglacial environments.
	2. On or beneath the Antarctic ice sheet **Priority – Underneath the ice sheet.** To advance understanding of subglacial geology. For example subglacial geology of East Antarctic interior to better understand supercontinent evolution, interior subglacial basins to obtain climate history records.
	3. In coastal Antarctica including at ice margins **Priority – Outcrops** at these locations are essential to visit. For example, the West Antarctic coast, particularly around the Amundsen Embayment and Marie Byrd Land, are relatively unknown. Access is available, but limited in time, in geographical access, and commonly tied to available ships.
	4. In the Southern Ocean / Deep Sea **Priorities – coastal to deep sea** records to study deep time climate history, ice-ocean interactions, and tectonic evolution of Antarctica/Gondwana. For example the Amundsen Sea, Wilkes Land, Ross Sea, and Scotia Arc are key targets by the marine geology community.
	For this group, large spatial areas need to be investigated to answer the science questions. Some of the questions in the cluster are best addressed in East Antarctica or West Antarctica target regions, though still over broad regional areas. Many are continental-scale questions.

<table>
<tr>
<td>What are the estimated costs of increased or new access to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?</td>
<td>Example cost access to interior of either West or East Antarctica: >10 million USD – Example cost estimate field camp providing access to interior West Antarctica: 35 million dollars for WAIS Divide Camp – deployment, several years of ice-core drilling and remote work from camp. Staffing for 2015-16 is 1.1 million, just doing ‘clean up’ of ice-core drilling camp, and supporting some other science projects. Example cost access to interior East Antarctica: AGAP – U.S. cost approx... 5 million USD/year for 2 years. PLUS funding by other nations, 5-7 million USD for 5 years of POLENET-scale network deployment/operations logistic costs.</td>
</tr>
<tr>
<td>If increased access is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?</td>
<td>Yes, all questions in the cluster would be addressed</td>
</tr>
<tr>
<td>Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be accessed to accomplish the science of this cluster. Include discussion of specific synergies with other clusters and cross-cutting Horizon Scan questions.</td>
<td> Priorities for Access – To study Dynamic Earth science questions, priority access is to the interior of the Antarctic Continent and, in particular, to the earth underneath the ice sheet. The need is to deploy remote sensor networks, drill and sample sediment and bedrock beneath the ice sheet, explore subglacial environments with sensors and remotely-operated vehicles, and conduct airborne and other field surveys. Accessing records beneath the seafloor is also a top priority, again including drilling and surveying to obtain deep-time records of climate and tectonic history. Many science objectives for Dynamic Earth require continental-scale observations. Synoptic observations from sensor networks and integrated drilling/sampling and survey campaigns are needed to reveal patterns of crust and mantle structure, geothermal heat flux, isostatic adjustment and dynamic topography, and rates of geomorphic change. Sectors of the continent and offshore marine realm can be targeted to address specific science questions. For example, networks and surveys over West Antarctica would best serve to investigate the role of volcanism in evolving lithosphere, changing climate and impact on ice sheets, whereas observations in East Antarctica are needed to better understand supercontinent assembly and breakup through Earth history. Marine subglacial basins and the offshore Amundsen Embayment region are key sites of synergistic exploration and sampling for the Dynamic Earth, Ice Sheets and Sea Level, Southern Ocean and Atmospheres science clusters.
Priorities for Infrastructure And Logistics – To succeed in accessing the deep interior of the Antarctic continent, deep-field infrastructure such as shared logistic hubs and transport networks are required. ‘Heavy class’ icebreakers are required to provide access to coastal stations, the core sites for bringing essential fuel, equipment and personnel to the continent, but also direct access to remote coastal margins and to execute shipborne research in ice-covered Southern Ocean waters. </td>
</tr>
<tr>
<th colspan="2">Highest Priority Infrastructure and Logistics</th>
</tr>
<tr>
<td rowspan="3">What are the highest priority enhancements in infrastructure and logistical support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements? See Survey results for descriptions.</td>
<td>Rank Order (1 is highest priority)</td>
</tr>
<tr>
<td> 1. Shared Logistic Hubs – that can be jointly supported by multiple nations, and offer science opportunities to scientists from many nations. The logistic hubs will entail/support:
a. Air transport
b. Ground traverse
c. Fuel depot(s)
These will support work in the deep interior and coastal areas of difficult access, in support of sensor deployments, surveys, drilling/logging and sampling. Such hubs should be capable of scaling, from small- to large-scale. Examine excellence in support elements in each national program and leverage opportunities to adopt these for support of shared logistic hubs. Note: ‘fuel is king’!
Direct infrastructure/logistics required for sensor deployments, field surveys in the Antarctic interior and on coastal margins:
a. Requires logistical hubs – typically both stations (delivery materials from off-continent) and deep-field camps.
b. Requires appropriate transport modes, for example ski-equipped aircraft and ground traverse capabilities inter- and intracontinental.
c. Requires field camp support for field team and transport personnel.
d. Requires deployment of fuel – both at logistical hubs and remote fuel caches.
e. Requires communications </td>
</tr>
<tr>
<td> 2. Icebreakers:
a. primary infrastructure for some ship-based activities, such as seismics, high resolution bathymetry mapping and deep-sea drilling in ice covered areas
b. can be primary infrastructure for access to coastal research sites
c. one element of primary infrastructure for many national stations which, in turn, constitute primary infrastructure for interior stations/logistic hubs
Note: different classes of icebreakers. ‘Heavy’ icebreaker (PC1-PC3) required. </td>
</tr>
</table>

	3. Polar Research Vessels: a. Access to coastal sites b. Deploy AUVs, ROVs, sensor networks c. Platforms for coring/drilling, deployment of seabed drilling systems d. Ship capable of launching ROVs/AUVs in ice-infested waters may be needed. e. Survey platform for marine environment
	Comment: Promote access to coastal and/or interior field sites from shared stations, or satellite stations linked with major national bases (i.e., each Treaty nation does not establish a new, small base in a region where many bases are already established). Several of the "new" regions of interest in Antarctica have not been investigated as much as the "easy areas" is both because of access but also other physical constraints such as poor weather. It is not only access but innovation (smarter) in the support for field operations such as drilling that is required in these difficult regions.
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All questions in this cluster.
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	**Shared logistical hubs** – particularly for access to remote regions that requires considerable logistical support such as the deep interior and isolated coastal. Supported by multiple nations who wish to take advantage of logistics available in a region, possibly working together on one project but could be on several different project topics but requiring similar logistics, e.g remote camp, sharing air transport as transport networks, ground traverse, fuel depots etc. Hubs should be capable of scaling from small to large scale. Requires excellent communications between partners on and off continent. Hubs would be temporary, lasting for as long as required for the project/s – for example, one or more seasons, staffed by various teams for longer seasons or year-round activity. Purpose – to deploy sensors, surveys, and drilling/logging/sampling – support all kinds of science. Advantages – better access, shared support not available to some projects/nations/. Shared costs, especially sharing fuel costs. Costs for hubs estimated from $1 – $10 million USD or more, depending on size and location. **Ships – icebreakers and polar research vessels.** a. Icebreakers (polar capacity PC1 to PC3) are primary infrastructure required for some ship-based activities, such as deep-sea drilling and marine research. Also for coastal research sites. Form one element of primary infrastructure for national stations for access. b. Cost: >$5 million USD (depends on class of icebreaker – range needed. c. Polar research vessels with ice capability required for access to coastal sites, to deploy AUVS, ROVS, sensor networks etc. Survey platforms for marine studies. Also used as platforms for marine coring/drilling, and deployment of seabed drilling systems. d. Cost: $500 USD million depending on specifications **Shared facilities/stations for National Programmes** Promote access to science targets via shared facilities at national stations (i.e. Nations planning new infrastructures should consider the advantages of cooperation/coordination with existing stations and logistical support. Infrastructures/logistics above would contribute to multiple science questions, not just one strand of science
Summary and Conclusions	
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Remote sensor networks (on the continent)
	2. Access to the interior of Antarctica
	3. Drilling ice and subglacial/ocean sediment and rocks
	4. Ships/icebreakers
	5. Drilling boreholes and sensors
	6. Shared field infrastructures
	7. Interoperability-multidisciplinary systems
	8. Samples, field surveys
	9. Improved power supplies
	10. Remote sensing satellite (off continent)

HORIZON SCAN CLUSTER 5:
Antarctic Life on the Precipice

ARC Workshop Writing Group Participants

Co-leads: Steven L. Chown & Yves Frenot
Rodrigo Mousalle Bueno, César A. Cárdenas, Don A. Cowan (Scribe), Gen Hashida, Marcelo Leppe, Daniela Liggett, Javier Negrete, Hyoung Chul Shin, Mario Proaño Silva, Sonia Ramos-Garcia, José Augusto Viera Da Unha De Menezes, Veronica Vlasich

Scientific Questions	*"Antarctic ecosystems were long thought of as young, simple, species-poor and isolated. In the past decade a different picture has emerged. Some taxa, such as marine worms (polychaetes) and crustaceans (isopods and amphipods) are highly diverse, and connections between species on the continent, neighboring islands and the deep sea are greater than thought. Molecular studies reveal that nematodes, mites, midges and freshwater crustaceans survived past glaciations. To forecast responses to environmental change we need to learn how past events have driven diversifications and extinctions. What are the genomic, molecular and cellular bases of adaptation? How do rates of evolution in the Antarctic compare with elsewhere? Are there irreversible environmental thresholds? And which species respond first?"* *Kennicutt et al., 2014 Nature COMMENT* The questions in this cluster fall into two main areas ((i) what is where and (ii) what is it doing), and that some of the technologies for addressing these two sectors can be very different (but some issues such as access issues, may be similar. The apparent omission of questions relating to Protected Areas (ASPAs) was raised and it was noted that the issues was absent largely because it is a current, and not a 20-year foresight, issue. The sub-Antarctic were considered as part of the larger Antarctic region of interest. However, the COMNAP recognizes 60° degrees South Latitude as the northern delineation of the region of interest. The outputs of the workshop are of value to COMNAP, SCAR and national programs and should therefore not be restrictive. Some national programs make no distinction between the Antarctic and the sub-Antarctic in operational terms while others may only allocate its resources to the geographic scope of the Antarctic Treaty and COMNAP.

Highest Priority Technological Advances

At What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Improved sensors, including new sensors, more robust sensors with automated calibration, sensor networks, and higher sensor resolution (system-dependent), for monitoring *in situ* structure (e.g. seal counts) and functional processes and compounds (including contaminants). Sensors are broadly interpreted to include those used sub-glacially to those flying on satellites. The calibration of new robust and long term sensors is needed.	H
	2. Robotic (controlled and autonomous) multi-purpose systems and vehicles for continuous and long-term *in situ* process monitoring and multi-sample recovery and return (including automated retrieval systems for recovering sensing equipment).	H
	3. Better and more integrated platforms for high performance computing, for rapidly growing 'big data' requirements. Such computing underpins modelling, automated image analysis and bioinformatics.	H
	4. High volume automated multi-omic platforms for phylogenetic and functional analysis of multiple large-scale meta-omic sample sets, including automated *in situ* metagenomic analysis and integrated bioinformatics analyses. A multi-omics platform might include automated sample extraction and clean-up, together with parallel NG sequencing of DNA, RNA and protein.	H
	5. High volume satellite/microwave bandwidth for integrating Antarctic data capture and both on-site and off-site analysis	H
	Comments: No substantial variances from survey results are obvious. It is noted that the priorities listed above are generally broader than those listed in the survey, in that they often simultaneously encompass several survey items. Few (if any) research technologies are 'Antarctic-specific', but are applied to an Antarctic location. Considerable overlap with ocean group (bandwidth, sensor technologies, including battery/energy requirements, robotic sampling and analysis). Much of what is considered has substantial implications for energy provision and energy intensity. The ability to efficiently manage 'Big data' is likely to be one of the greatest impediments to the future progress of Antarctic biological research.	

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Sensors – many do not yet exist (at a suitable sensitivity, robustness, in arrays etc). Development ongoing (5 – 10 years?). Some may be Antarctic-specific. 2. Robotic platforms – exist for marine systems but not for terrestrial systems. Different timescale for the two systems. For the former, need further development (5 years), especially for retrieval operations; for the latter, 5 – 15 years (except UAVs, which are relatively advanced). Some terrestrial robotic systems do exist (which address other questions (such as access) – relevant to safety of traverses). 3. Larger and faster computational platforms for 'big data' analysis. Under development, with continuous evolution. More a cost and availability issue. 4. Multi-omic platforms ((e.g. for genomic, transcriptomic, metabolomic etc. research) and associated software. Under development by big international companies, but 5 – 10 years to implementation. 5. Enhanced bandwidth for big data transfer. Microwave/optical fiber/satellite support: Many new technologies are under development; current – 10 years
At what temporal scales will these **technologies** most likely be used and how frequently?	1. Sensors – all temporal scales (from continuous to intermittent) 2. Robotic platforms – all temporal scales (from continuous to intermittent) 3. Computational platforms – continuous 4. Multi-omic platforms – intermittent. Will vary from group to group. Multi-use platforms are feasible. 5. Enhanced bandwidth – continuous
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Impossible to estimate specifically (from tens of thousands to multi-millions) depending on type of sensor and the objective (e.g., sub-glacial lake sensors are under development; but others will be developed globally) 2. Highly variable. E.g., UAV development costs are low, c.f., very high (see cost of development of Mars Rovers) 3. Computational platforms – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue. 4. Multi-omic platforms – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue. The greatest cost to the user is the training (particularly of bioinformatics researchers). 5. Developments are undertaken by large communications organizations. For Antarctic researchers, this is a user cost, not a development cost, issue. COMNAP has an important role in coordination and information exchange within and between national Antarctic programs. Developments led by Arctic communities.
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/ which questions (by Horizon Scan number)?	All of these technologies support multiple scientific questions. a. For Sensors: Q43, 45, 47, 49, 50 – 53, 60 – 63, 65 b. For Robotic platforms: 43, 44, 48, 49, 50, 51, 54, 57, 58, 60, 62, 63, 65 c. For Computational platforms: 43-46, 49, 53-55, 57, 59, 60, 62, 64-68 For multi-omic platforms: 43-45, 47, 52-58, 64, 67, 68 For high band-width communications: all questions
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	a. All the biggest technological challenges are beyond the control (i.e., independent design and construction) of the National Antarctic programs, in that these are generic challenges applicable to research which extends to systems far beyond the Antarctic sphere. Few of these challenges are likely to be developed solely for the Antarctic (for example, terrestrial robotic platforms can be used in other extreme environments – polar, alpine, desert, etc.). b. Adaptations of existing technologies may be the most efficient method for designing Antarctic-specific platforms c. By comparison, these are not beyond the 'capability' (use) of National Antarctic programs – i.e., they will be used by such programs. d. For computational platforms, these technologies are well within the capabilities and control of the National Antarctic programs. e. For multi-omic platforms (i.e., for genomic, transcriptomic, metabolomic research), the same applies. However, the capability issues for in situ platforms (requiring support from companies and agreements between national programs). It was noted that the technology developments may change personnel balances (more technicians). f. For high speed/volume communication systems, these are completely within the capabilities/ control of national Antarctic programs.

Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Antarctic researchers are usually cognizant of new technologies as they arise, and constraints may be more related to the availability of funds than lack of awareness. Some very innovative and relevant technologies may not yet be publically available (i.e., those that are developed initially for military purposes). There technological developments that might exploit Crowd Sourcing approaches using cell phones in Antarctic monitoring and surveillance.
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	Life on the Precipice covers environments from the subglacial to the marine, to terrestrial systems, and spans as wide a range of organisms, from bacteria to marine mammals, and encompasses a wide variety of themes in biology and ecology. Given this diversity the key technologies required are sensors for both structural (species detection) and functional (e.g. nutrients, CO_2) purposes to be used in environments from subglacial to marine, and including sensors for use on satellites to UAVs. Recognizing that field personnel will always be a key part of any program, much of the work required to address these new questions will require automated sampling and robotics. The Omic approaches (e.g. genomic, transcriptomic, metabolomic) will form a key part of this work. In situ omic platforms which allow real-time analysis and onward transmission of data (rather than samples) will require deployment across a range of sites, keeping up with developments globally. Modelling, bioinformatics, ecoinformatics and associated approaches will require increasing access to high performance computing. Accessibility of such computing, both in the Antarctic and at home institutions is essential. High speed communication via satellite, microwave and other technologies will be a significant technological requirement to deliver the science for Life on the Precipice. Such communication includes capabilities from ships given their ongoing significance for deep sea work and the requirements for integration of data from AUVs, gliders and equivalent instrumentation. The issue of technology scanning (by Antarctic researchers) should be on-going and proactive, so as to take advantage of the latest and most sophisticated technology. COMNAP should establish a scanning group to look for new technologies relevant to their remit (with respect to energy, science, and communication). Many questions will be more readily answered if SCAR promotes a high level of integration between relevant organizations. COMNAP and SCAR should ensure that mechanisms for transfer of knowledge and exchange of personnel are available.
Highest Priority Access to the Antarctic Region	
Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of **access**?	**Rank Order (1 is highest priority)**
	1. Coastal regions of terrestrial Antarctica and the sub-Antarctic islands
	2. Access from the ocean to the land (including ice-breakers, sea-ice transport technologies, air transport)
	3. Deep sea access (including vessel capability, remote vehicles)
	4. Development of 'transitory' (modular, mobile) facilities for temporary support of research activities
	5. Extended temporal access (through winter) to Antarctic sites (note cross link to remote technologies)
	Comments: a. It was argued that the most important biological questions can be mostly addressed by access to areas where research is already undertaken (existing bases etc.). b. It was also argued that the most important element of access is often not physical, but is actually access to data (i.e., increased data-sharing). c. The group suggests that a discussion with the marine community on aspects of access, including deep marine access, is necessary d. The group notes that Q55 required access to all regions of the Antarctic continent, the southern oceans and the sub-Antarctic islands
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Coastal regions (existing sites and locations)
	2. Access from the ocean to the land
	3. Deep sea access
	4. Development of 'transitory' facilities
	5. Extended temporal access
	Comments: The costs range is huge for each of the items: it will range from project grant cost levels (thousands) to, for example, joint cooperation for design and construction of new vessels (multi-millions). In some cases, costs can be reduced by a greater degree of coordination between national Antarctic programs, including the sharing of station facilities. The concept of a regionally based 'fleet coordination' approach for oceanography and base support would be highly beneficial.
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)	Yes. As this covers temporal and special data issues, all questions are relevant.

Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access**ed to accomplish the science of this cluster.	Much of the access to Antarctic habitats, particularly terrestrial habitats, required to answer the Horizon Scan questions, does not require vastly extended logistics to support access to remote sites. Much of the research required to answer most of the questions posed can be done at sites which are currently intensively studied. That said, there is a clear need for expansion of current studies from two dimensions to four – expanding to increase the physical depth of analyses and to cover a much wider temporal range, currently mostly restricted to a relatively short summer season. The requirement to increase the understanding of the range and diversity of Antarctic terrestrial biota does, however, also require access to remote areas and to specific habitats (such as intra- and sub-glacial ice habitats). Some of this need could be serviced by the development and use of mobile modular (transitory) facilities. Access to marine habitats has more substantial access requirements, but overlaps very substantially with the requirements of the physical sciences researchers (oceanographic, glaciological, and geological). Many of the Horizon Scan questions require comprehensive access to all areas of the circum-continental oceans, including many which are currently poorly accessed (sub-sea ice, sub-glacial and ice-shelf, deep marine) and a substantial extension the temporal access (from seasonal to year-round). The most dominant theme of the discussions was a complete consensus on the enormous benefits of science-driven collaboration. Such collaborations offer a very wide range of 'access' advantages, including access to field sites, technologies, skills and resources and, above all, data. The group concurred that the benefits of data sharing between researchers across all national platforms provides an effective mechanisms for promoting Antarctic research across all subject areas.
Highest Priority Infrastructure and Logistics	
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)** 1. Improvement of modularity in facilities (mobile, collaborative). 2. Coordination of existing ship and marine logistic operations. 3. Upgrade and enhancement of power delivery (in a renewable manner). 4. Improved cleaning technologies for Antarctic research and support operations in both marine and terrestrial environments to reduce contamination, transfer of biological materials etc.
What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. High cost (sub-millions) 2. Low cost (but high organizational burden) 3. New technology required – cost estimates difficult 4. New technology required – costs probably not excessively high.
If available, will these infrastructure and **logistical needs support multiple** scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	In general, the proposed infrastructure and logistical elements would support, in one way or another, all the questions in the cluster. For example, the development of mobile and modular facilities can potentially be used for research addressing virtually any of the questions listed under the Life on a Precipice heading.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster *n Scan questions.*	Reliable access to terrestrial, freshwater and marine environments by researchers is a key requirement for delivery of Life on the Precipice. While automated sampling and robotic sampling will require development to extend reach both through time and across space, the presence of personnel in the field, extending across full years, will remain essential. Indeed this need will grow as understanding of the full season grows in significance. Access to all areas is required, though coastal regions remain a priority for terrestrial work. Improved deep sea access is clearly essential. Marine infrastructure to provide access to ocean areas from shallow sites, especially those that are hardly accessible under the permanent sea-ice and ice shelves the deep sea on an ongoing basis requires consideration. The development of modular facilities both for terrestrial and marine work is an essential component of new infrastructure development. Such modular facilities will enable access to new areas for longer periods without the need for expensive permanent infrastructure. Addressing the questions will require increasing power at a range of both station sites and remote localities. Such power delivery in a renewable way will be a key logistic/infrastructure need. An increasing focus on green technologies will be essential to deliver the science with minimal environmental compromise. Ensuring that transfer of material or propagules among sites, which would compromise the environment and the ability to understand evolutionary processes, will not happen is essential. This will require new developments in the provision of clean gear or cleaning technologies, at the scale of individuals to ships, aircraft and vehicles. Many of the infrastructure requirements can be substantially addressed by improved collaboration and strategic sharing of resources. This might include sharing of station facilities, joint planning and coordination of regional shipping to address simultaneously logistic and research needs, and shared air operational discussions. Access needs to high performance computing and multi-'omics' platform infrastructure can be addressed through personnel exchange, science-driven collaboration, and joint planning of research. Many of the issues raised above relate to access processes, often to remote and difficult areas, and collaboration between programs is likely to be a key element of addressing infrastructure needs.
Summary and Conclusions	
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Enhanced collaboration, including improved data sharing and access to stations, logistics and operational activities is a critical requirement for future Antarctic research (see Article III of the Antarctic Treaty) 2. It is important to balance the differential skills, capabilities and capacities across different national platforms, particularly in the fast-developing and technology-intensive research sectors, through better resourcing of researcher exchange programs (and capacity building) via multiple mechanisms including scientific collaborations. 3. New technologies for autonomous and robotic sample and data recovery, in order to expand sample acquisition over both much wider spatial and temporal scales, is a high priority. 4. Acknowledging that autonomous systems will not always is sufficient for data and sample acquisition, guaranteed access for scientific personnel to a wider Antarctic area, and extension of that access to encompass much wider temporal scales, is a priority. 5. Many of the anticipated advances in technology (whether diagnostic, surveillance, diversity research or ecological function) will result in very large datasets. The need for access to much greater computational power and speed, will be critical for future Antarctic research. 6. There is value in coordination and collaboration between different disciplines. Infrastructure and logistics designed for one objective (e.g., sub-sea ice marine water surveys) will be appropriate for other objectives (e.g., biological surveys). 7. Investments into the development of new sensors and sensor technologies are considered to be a very high priority. 8. The development of new technologies should aim to minimize environmental impacts, including the minimization of human impacts. 9. Data generation in Antarctic research will increase dramatically and it will be critical to increase bandwidth and communication capacities within and from Antarctica. 10. Joint work in key research areas involving large collaborative projects. Many of these questions require joint collaboration on infrastructure, access and logistics that is science driven.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	The dramatic developments in the 'omic' technologies have the capacity to transform Antarctic biological research over the next 1-2 decades. The opportunities for collaboration (sharing of research objectives, infrastructure, field program, data analysis etc), if supported and managed effectively, could have an equally dramatic effect on future Antarctic research.

HORIZON SCAN CLUSTER 6:
Near-Earth Space and Beyond

ARC Workshop Writing Group Participants

Co-leads: John Storey & Allan T. Weatherwax

This Writing Group report was not written at the workshop. The report was written on behalf of representatives from the SCAR Astronomy and Astrophysics from Antarctica Scientific Research Program and from the Sun Earth Relations community of SCAR.

Scientific Questions	*"The dry, cold and stable Antarctic atmosphere creates some of the best conditions on Earth for observing space. Lakes beneath Antarctic glaciers mimic conditions on Jupiter and Saturn's icy moons, and meteorites collected on the continent reveal how the Solar System formed and inform astrobiology. We have limited understanding of high- energy particles from solar flares that are funneled to the poles along the Earth's magnetic field lines. What is the risk of solar events disrupting global communications and power systems? Can we prepare for them and are they predictable?"* Kennicutt et al., 2014 *Nature* COMMENT Life in the Universe: One key question overlooked in the Horizon Scan is whether or not life exists elsewhere in the Universe. Although touched on peripherally by Question 47: ("How do subglacial systems inform models for the development of life on Earth and elsewhere?"), it is a crucial question in its own right; one that should be answerable within the next three decades. Investigating what form that life takes, and how it has evolved separately from life on Earth, is one of the most exciting endeavors for the future. Space Weather and Climate Change: Question 72 states "How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere?" This question, together with Q47 above, should receive further attention. Changes occurring in interplanetary space have a profound effect on the upper atmosphere, especially at the poles. One needs to understand the physics linking the space environment to that of Antarctica, and how this subsequently influences the global atmosphere. Effects associated with solar variability, perhaps through auroral precipitation, are thought to perhaps impact climate change.	
Highest Priority Technological Advances		
What are the highest priority **technological** needs to answer questions in this cluster?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. High bandwidth networks on/off continent and continual data transfers in real time from locations throughout the Antarctic.	H
	2. Energy efficient high-performance computing hardware and advanced data analysis techniques.	H
	3. Remote/robotic observatories optimally and strategically deployed across the plateau.	H
	Comments: Overall, pressing technological issues that must be resolved in order to address the science goals include: • Energy efficient high performance computing hardware. • Large data storage devices able to withstand the low atmospheric pressure on the high plateau, and possible cold-soaking (extreme conditions). • Low power consumption cryo-coolers capable of maintaining instruments at 4K and below. • Renewable energy technology such as wind turbines able to operate efficiently on the high plateau, with low wind-speeds, low atmospheric pressures, and very low temperatures. • Development of a diesel power pack at the tens of kW level that has low particulate emission, and can operate unattended for 1 to 2 years.	
What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	These technologies listed above are all in a state of continuous development. They are available in some form or another at present. There is no "end point". See the Autonomous Polar Observing Systems (APOS) workshop report for further details.	

At what temporal scales will these **technologies** most likely be used and how frequently?	1. continuous	
	2. continuous	
	3. continuous	
	Comments: These technologies are all in a state of continuous development. They are available in some form or another now, and are currently being used. There is no "end point".	
What are the estimated costs to develop/deliver the highest priority **technology** needs?	These technologies are all in a state of continuous dvelopment, there is no "final cost", but rather an ongoing development cost. The overall cost is of the order of a 1-10 millions of dollars per year.	
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	These technologies are important for all of the questions listed including 69-73 and Q47. Recent advances in critical engineering and logistic support will help continue to facilitate the objectives in this cluster.	
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	Both the energy efficient high-performance computing hardware and the high bandwidth networks are under development for other purposes in industry and science. In addition, specific technologies are under development for astronomical purposes alone, such as the development of novel interferometric telescopes. However, for the most part, it is technological advances for broader purposes that are adopted by astronomers and space scientists for their needs.	
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	There are no obvious technological capabilities currently available that are not being employed or considered for use in Antarctica	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster.	There is a clear trade-off between communications bandwidth and capability for on-site data processing. The former is dependent on the infrastructure provided by the national programs, the latter requires either significant advances in energy efficient high-performance computing hardware and/or the availability of more electrical power. To fully answer the questions related to the Dark Universe and extra-terrestrial life requires the deployment of optical/infrared telescopes. A key issue is that the science drives us towards a telescope that is too large to deploy until the engineering risks have been retired through a series of pathfinder experiments. Identifying funding sources for such pathfinders is a critical challenge. Large single-dish telescopes will require novel telescope designs (e.g., segmented mirrors), in order to be transportable to remote locations. Technologies to facilitate this might include off-axis mirrors, lightweight (carbon fiber) mirrors, and high precision inertial pointing systems. Research in the polar regions also supports the high-latitude observations needed to understand fundamental aspects of coupling between the solar wind and Earth's atmosphere, ionosphere, and magnetosphere. The vast geographical regions in both hemispheres provide access to a broad range of geophysical phenomena, spanning magnetic and geographic latitudes from the sub-auroral zone to the polar caps, at altitudes from the troposphere to near-Earth space. While the northern hemisphere is relatively well Instrumented with regards to near Earth space observations, the southern polar region is not, primarily because of the extreme Antarctic climate and the lack of manned facilities with infrastructure. The situation in the southern hemisphere, however, is changing with the development of technologies that support autonomous measurement systems that can be deployed in remote locations and operate unattended for long periods of time in severe environments.	
Highest Priority Access to the Antarctic Region		
Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. South Pole station	M
	2. Balloon platforms	M
	3. High plateau sites remote and permanent stations.	M
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	The overall costs are not known. However, development is underway by several SCAR countries on each item listed.	
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	For Eyes in the Sky and near Earth space observations, all three areas are important for all three of the questions.	

Highest Priority Infrastructure and Logistics		
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)**	**Confidence (H,M, L)**
	1. Wide bandwidth, continuous communications infrastructure	
	2. Air access to high plateau.	
	3. Power generation capability of tens of kW at remote sites	
What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	Responses are predicated on the assumption that there will be continued support, at least the current level, of South Pole and McMurdo infrastructure, including the continued development of long duration ballooning. There is also concern about the long-term availability of the large quantities of helium needed for balloon platforms.	
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	All three infrastructure/logistics areas are important.	
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	The greatest challenges to be faced are the ever-growing energy requirements and the need for greatly increased data transfer rates. For example, future neutrino experiments at South Pole are anticipated to need off-continent data transfer of 1000 GB/day (compared to 150 today), while 24-hour coverage will be important for future Cosmic Microwave Background experiments. **South Pole station** Electrical power and data-transfer rates are key challenges. As extended neutrino detector arrays are deployed, delivering hundreds of watts of power to the array stations up to 10 km away remains problematic. As detectors grow to occupy areas of up to 1000km2, autonomous power systems may provide the only solution. **High plateau sites** Future logistic support of experiments on the high plateau might be done in a number of (non-exclusive) ways. Existing stations (Domes A, C, and F) can further develop their support capabilities, autonomous field observatories such as Ridge A might continue to grow as fully-fledged robotic stations, and one or more new high-plateau sites could be opened up.	

Workshop Goal #4 – Summary and Conclusions	
What are the top 10 "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Logistical access to the Antarctic Plateau (e.g., flights).
	2. Technological access to the Antarctic Plateau (e.g., remote/robotic observatories).
	3. Real-time data access across Antarctica is critical.
	4. Wide bandwidth, continuous communications infrastructure.
	5. Continued support for Long Duration Balloon flights.
	6. South Pole and other manned stations need infrastructure upgrades to power and data systems.
Comments	Input to this report comes from the responses to the two ARC/COMNAP surveys, plus a white paper on the technological challenges and logistical needs of the Antarctic astronomy and astrophysics community that resulted from a dedication discussion held amongst 40 members of the SCAR AAA community on 10 August 2015. Further input was obtained from the report entitled Solar-Terrestrial Research in Polar Regions: Past, Present, and Future National Science Foundation grant PLR-1258007] and the report from the Autonomous Polar Observing Systems (APOS) workshop, held at the Bolger Center in Potomac, Maryland on September 30- October 1, 2010. The Sun Earth Relations community of SCAR via the action group SERAnt also provided valuable input.

HORIZON SCAN CLUSTER 7:
Human Presence in Antarctica

ARC Workshop Writing Group Participants

Co-leads: Steven L. Chown & Yves Frenot
Rodrigo Mousalle Bueno, César A. Cárdenas, Don A. Cowan (Scribe), Gen Hashida, Marcelo Leppe, Daniela Liggett, Javier Negrete, Hyoung Chul Shin, Mario Proaño Silva, Sonia Ramos-Garcia, José Augusto Viera Da Unha De Menezes, Veronica Vlasich

<table>
<tr><td>Scientific Questions</td><td>“Forecasts of human activities and their impacts on the region are required for effective Antarctic governance and regulation. Natural and human impacts must be disentangled. How effective are current regulations in controlling access? How do global policies affect people’s motivations to visit the region? How will humans and pathogens affect and adapt to Antarctic environments? What is the current and potential value of Antarctic ecosystem services and how can they be preserved?” Kennicutt et al., 2014 Nature COMMENT

It is noted that the survey results show a sampling bias, given that relatively few social scientists were respondents (although probably reflecting the proportion of social scientists in the larger Antarctic research community) resulting in a very marked focus on technological emphasis (as was the intention of the survey).
Responses 1-3 below are aligned with answers to Life on a Precipice.
It is recommended that COMNAP continue to address the issue of global data sharing from publically funded research.
Most questions in the Human Presence cluster require improved access to data (including archival material), but not all of them require specific technology (other than commonly available data storage and database capacity, high-speed internet connection and certain software used for data analysis, e.g. NVivo and ArcGIS).
While this report focuses on those questions that have specific technological requirements, this is not meant to undermine the importance of questions (e.g. around governance and regulation) without particular technological requirements.
The White Paper submitted to the ARC Workshop by the SCAR Humanities & Social Sciences and History Expert Groups contains details on specific structural and methodological peculiarities and requirements of social sciences and humanities research in relation to the SCAR Horizon Scan questions.
</td></tr>
<tr><td colspan="2">Highest Priority Technological Advances</td></tr>
<tr><td rowspan="7">What are the highest priority technological needs to answer questions in this cluster?</td><td>Rank Order (1 is highest priority)</td></tr>
<tr><td>1. Advanced data analysis techniques (HP computing) and improved bandwidth</td></tr>
<tr><td>2. Improved ecosystem models</td></tr>
<tr><td>3. New and better sampling and handling technologies</td></tr>
<tr><td>4. Better sensing and surveillance technologies and tracking systems, including autonomous tracking devices and smart technologies (e.g., for vessels, for landings, for land vehicles, for scientific expeditions and other land-based human activities such as camp sites)</td></tr>
<tr><td>5. Imaging and recording equipment suitable for use in extreme climate conditions</td></tr>
<tr><td>Comments:

Responses 1-3 above align with Life on a Precipice. For item 4, some of these data exist, but coordination of data capture and storage, and the sharing of data, are both poorly organized. To thoroughly respond to the Horizon Scan questions in the “Human Presence” cluster developments outside the Antarctic domain influence the context (or even determine the questions) and are a significant influence. Social scientists’ and humanities scholars’ attention to ‘Antarctica’ includes activities beyond Antarctica. The technological requirements for data collection and analysis described need to reach beyond the Antarctic realm.</td></tr>
</table>

What is your estimation of the current status of the highest priority **technological** needs – do they exist, are they widely available, and what is the stage of and time required for development if necessary?	1. Advanced data analysis techniques (HP computing) – larger and faster computational platforms for 'big data' analysis. Under development, with continuous evolution. More a cost and availability issue.
	2. Improved ecosystem models – actually dependent on computational capacity (see above).
	3. Sampling and handling technologies: For example, robotic platforms exist for marine systems but not for terrestrial systems. Different timescale for the two systems. For the former, need further development (5 years), especially for retrieval operations; for the latter, 5 – 15 years (except UAVs, which are relatively advanced). Some terrestrial robotic systems do exist (which address other questions – such as access).
	4. Better sensing and surveillance technologies and tracking systems – the technology mostly already exists, so this is an issue of implementation and sharing of the resulting data.
	5. Imaging and recording equipment suitable for use in extreme climate conditions – already widely available (some adaptations may be required)
At what temporal scales will these **technologies** most likely be used and how frequently? See the Survey for temporal scales to be used.	1. Advanced data analysis techniques (HP computing) – continuous
	2. Improved ecosystem models – see above
	3. Sampling and handling technologies – intermittent to continuous (depending on the nature of the sampling objectives and technologies)
	4. Better sensing and surveillance technologies and tracking systems – usage is continuous
	5. Imaging and recording equipment suitable for use in extreme climate conditions – usage depends on the nature of the research objectives and imaging/recording technologies
What are the estimated costs to develop/deliver the highest priority **technology** needs?	1. Advanced data analysis techniques (HP computing) – the development cost is very high, but development is undertaken by international companies and organizations, and the user costs are reducing. This is an access cost issue, not a development cost issue.
	2. Improved ecosystem models – impossible to estimate (other than a requirement for larger computational capacity) – probably a human resource issue
	3. Sampling and handling technologies – Highly variable with respect to autonomous sapling platforms. E.g., UAV development costs are low, c.f., very high (see cost of development of Mars Rovers)
	4. Better sensing and surveillance technologies and tracking systems – relatively low cost technology
	5. Imaging and recording equipment suitable for use in extreme climate conditions – relatively low cost technology
Will these **technologies** support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	1. Advanced data analysis: Q74, 75, 79, 80
	2. Improved ecosystem models: Q74, 75, 79, 80
	3. Improved sampling and handling technologies: Q74, 75, 79, 80
	4. Better sensing and surveillance technologies and tracking systems: Q74, 75, 78
	5. Imaging and recording equipment: Q75, 76, 78
Are there **technological** challenges identified that you believe are beyond the capabilities/control of National Antarctic Programs (e.g., major technological breakthroughs unlikely to be solely developed for use in Antarctica)?	All the biggest technological challenges are beyond the control (i.e., independent design and construction) of the National Antarctic Programs as these are generic challenges applicable to research which extends to systems far beyond the Antarctic sphere. Few of these challenges are likely to be developed solely for the Antarctic (for example, terrestrial robotic platforms can be used in other extreme environments – polar, alpine, desert, etc). Adaptations of existing technologies may be the most efficient method for designing Antarctic-specific platforms. However, the implementation of surveillance and tracking technologies and processes is completely within the capabilities/control of National Antarctic Programs.
Are there **technologies** and/or capabilities currently available that have not been used in the Antarctic that would have a transformative effect on research in this cluster if they were available?	Antarctic researchers are cognizant of new technologies and constraints may be more related to the availability of funds than lack of awareness. Some innovative and relevant technologies may not yet be publically available (i.e., those that are developed initially for military purposes). Surveillance and tracking technologies widely used elsewhere could be rapidly and readily translated to the Antarctic (where they currently do not exist). Imaging and recording equipment is widely used and relatively readily available but may have to be adapted to be suited for use in Antarctica's extreme conditions.

Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **technological** needs to accomplish the science of this cluster. *Include discussion of specific synergies with other clusters and cross-cutting Horizon Scan questions.*	Human Presence encompasses a diverse set of questions that integrate the life sciences and a range of social sciences and humanities disciplines, including anthropology, economics, history, human geography, law, political sciences, and social psychology. The integration of methods of inquiry from such a wide range of disciplines requires (a) the availability of suitable technologies, and (b) the reduction of barriers to access to materials, actors and systems that go beyond technological requirements. The technologies required to address the Human Presence questions are similar to those for Life on the Precipice. High performance computing for advanced modelling both in the life and social sciences is a key requirement. Better sensors, and more broad deployment, both in space and time, of such sensors, including robotic and automated sampling, will be required to understand impacts. For example, understanding new contaminants, the arrival of new species, and the impacts of both requires such sampling. In marine systems, automated systems for understanding fishing impacts will be essential, coupled with information on the scope and extent of such resource extraction. Sensing, surveillance and tracking systems to provide information on movements of vehicles of all kinds, and to understand volume of visitor access to various sites require deployment and in some cases development. At the same time, it is worth noting that attention should also be paid to technologies that would assist in mapping and assessing existing material legacies (e.g. building remains or artefacts) in the Antarctic in a coherent and systematic manner. While improved sensing and robotics technologies are essential to address the environmental science aspects of questions in the Human Presence cluster, there is also a pressing need to overcome barriers to data access. To effectively address the questions related to human impacts and governance, detailed information about human activities in the Antarctic – from science operations to tourism to fishing and other commercial activities – that is recorded by the operators or facilitators of human activities in Antarctica needs to be accessible. In conclusion, for many of the more humanities and social science focused questions, the key technological constraints are small. However, access to the continent for social scientists and humanities researchers as well as access to information and improvement of this access are significant. An element of this access goes to the need to improve understanding of the need for use of privileged information. The humanities and social sciences have well-developed codes of practice for the use of such information. Importantly, little progress will be made on several of the key questions without better general appreciation of the need for the collection and provision of such data – even if the latter are through very specific contractual agreements.

Highest Priority Access to the Antarctic Region

Which are the highest priority areas of the southern polar regions for increased or new **access** to accomplish the scientific objectives of this cluster and what is the status of access of **access**? See Survey results for location descriptions.	**Rank Order (1 is highest priority)** 1. Coastal regions of terrestrial Antarctica and the sub-Antarctic islands, particularly high 'intensity' sites (research and tourist) 2. Remote ice-free areas of the continent 3. Access to the maritime domain with ships
What are the estimated costs of increased or new **access** to the highest priority areas of the southern polar regions needed to accomplish the scientific objectives of this cluster?	1. Cost estimates are relatively low (for access issues) because the sites identified are those which are already heavily supported by national logistics and related research activities 2. Logistic costs are high (given the complexity of logistics support) 3. Cost estimates are relatively low as maritime areas are readily and regularly accessed by ship (cruise ships, research vessels, fishing vessels)
If increased **access** is available will it support multiple scientific questions in this cluster? If so, how many/which questions (by Horizon Scan number)?	All questions (possibly excepting Q76), are relevant to all priorities.
Provide a short (<500 words) narrative summarizing your conclusions describing the highest priority areas of the southern polar regions that need to be **access**ed to accomplish the science of this cluster.	a. Understanding anthropogenic change relative to other change may require access both to current and new remote sites. Much of the access needs for this question can be met through current arrangements, though these may change as the spatial and temporal extent of science and tourism in the region changes through time. The requirements are essentially of an interactive form, where changes in some areas will be required to meet changing research and access approaches. b. Ongoing access by social science and humanity researchers to field sites is essential. Much of this will require consideration in planning such work in coordination with other activities. c. Access to high impact sites and to new sites will be required to understand the ways in which changing patterns of activity are impacting the environment and how successful various arrangements are in addressing these impacts. d. Access to the maritime domain is essential as the highest volume of people access Antarctica by sea. Whether investigating biophysical or social sciences facets of research, tourism or marine harvesting activities, access to the maritime domain is critical. e. For deep sea impacts a range of autonomous vehicles as well as ship capability will continue to be required. Near-shore and benthic access across a range of areas remains essential.

Highest Priority Infrastructure and Logistics	
What are the highest priority enhancements in **infrastructure and logistical** support needed to accomplish the scientific objectives of this cluster and what is the status of these enhancements?	**Rank Order (1 is highest priority)** 1. More collaboration between national Antarctic programs, including logistics sharing. 2. Equal opportunity for social sciences and humanities scholars to Antarctic field programs. 3. Improved coordination of data collection, data storage and access to information.
What are the estimated costs of providing enhanced the **infrastructure and logistics support** needed to accomplish the scientific objectives of this cluster?	1. Costs may be relatively low, as collaborative activities may be 'buried' within national Antarctic program budgets 2. No additional costs are anticipated, as this element is embedded in existing programs
If available, will these **infrastructure and logistical** needs support multiple scientific questions in this cluster? If so, how many/which ones (by Horizon Scan number).	Relevant to all questions
Provide a short (<500 words) narrative summarizing your conclusions about the highest priority **infrastructure and logistical** needs to accomplish the science of this cluster.	A key infrastructure and logistic requirement to answer questions included in Human Presence in Antarctic is science-driven collaboration. This includes collaboration and cooperation among states, among stations, among disciplines. It also includes collaboration with humanities scholars and social scientists working in the Arctic and sub-Arctic, where understanding human presence is arguably more established. Access to information and to sites will be essential, along with development of logistics to ensure that best use is made of opportunities that emerge from the full range of science and logistic activities.

Summary and Conclusions	
What are the top "take home messages" from your discussion, i.e., the "big issues" including those investments of monies and resources that have the highest likelihood of producing the maximum scientific return?	1. Increased investment in survey capabilities/tracking (of human and vehicle activities, propagule transport, establishment, survival, contamination, etc) relating to anthropogenic impacts is important 2. Enhanced collaboration, including improved data access and sharing, is a critical requirement for future Antarctic research (see Article 3 of the Antarctic Treaty) 3. Researcher exchange programs (which includes a trans-polar exchange of researchers) are essential for delivering the research in this cluster. 4. Greater access for researchers to other researchers, stations, logistics and operational activities and Antarctic programs, across national boundaries, is essential 5. Enhanced sharing of technology is critical, especially in consideration of the fact that in some countries access to high-speed internet or data storage is not commonly available. 6. The research insight benefits from equal opportunities access by for the social scientists and humanities researchers to the continent to gain access to the continent (removing barriers to access and enhancing capacity building). 7. Considering that the Antarctic humanities and social sciences are still at a capacity-building stage, they are in need of more opportunities to collaborate, more national and institutional acknowledgement of their contributions to empirical understandings of the human presence in Antarctica and more funding opportunities specific to the methodological approaches taken by humanities scholars and social scientists. 8. Researchers from the humanities and social sciences should be afforded equal opportunity of access to Antarctic field programs.
Are there important long-term trends in technology and science delivery requirements that have the potential to transform Antarctic science and its support over the next two decades?	New diagnostic technologies, including 'omics' technologies, will have a dramatic effect on our ability to detect, monitor and predict the effects of human activities on and around Antarctica.